PRACTICAL PHYSICS

FOR B. SC. PASS COURSE

BY

DR. D. P. RAY-CHAUDHURI

AND

PROF. DIPAK RAY

A. MUKHERJEE & CO. PVT. LT

Written in conformity with the syllabi of Calcutta, Burdwan,
North Bengal and other Indian Universities

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For B. Sc. Course

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PREFACE

Written in easily intelligible English the book covers the 2 yr. Degree syllabi of the Universities of Calcutta, Burdwan, North Bengal and other Indian Universities. The experiments given in the book have been grouped according to the branch of Physics they belong to.

At the begining of every experiment *a list of apparatus and accessories* required for the work has been given. As it is not possible to describe all the different types of apparatus required for an experiment within the small compass of this book, we have described only those that are more common and are used more often.

For every experiment, *detailed instructions* have been given about how to do it. A brief statement of *the method followed* in making an experiment has been given to help the student *write up* the experiment. *Precautions* that need be taken before working out an experiment have also been given to make the student cautious before proceeding with his experiment.

In cases where *Experimental data and results* can be recorded *in a tabular form*, the form of the table has been given. In some cases the steps in an experiment have been illustrated with *diagrams* and / or *graphs.*

In many cases before discussion of an experiment, *some relevant basic matters*, e.g., *theory*, *etc.* have been given to provide the student with some working idea about some principle, some instrument etc.

Oral questions are usually asked during a practical examination to test whether the student is doing the work intelligently or mechanically. To give the student an idea of the nature of questions that he may be asked to answer and how best he should answer them, quite a number of probable *oral questions* with *answers* have been given at the end of each experiment.

Quite a number of *Tables* showing densities of common substances, breaking stresses of common laboratory materials, density of water, elastic constants, saturation vapour pressure of water etc., as also log and anti-log tables, tables of natural tangents etc. have been appended to the book which, I am sure, will enhance its usefulness to the students.

We are fully aware of the difficulties that a student usually faces in doing an experiment and this book, we trust, will remove their difficulties and make their task easy.

The first edition of a book, in spite of all possible care being taken, is likely to contain errors and ommissions. Intimation of any such error or omission will be gratefully acknowledged, as also any suggestion for improvement.

July, 1985

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CHAPTER I | INTRODUCTORY

1-1. Eye-estimation. The work of a student in the laboratory generally consists in finding the value of a certain *quantity.* This he does by measuring a number of other quantities which are connected with the former by a definite formula. The quantities he measures *directly* may be a mass, length, time, volume, temperature, current, potential difference, etc. In all these cases, *the observation finally reduces to the reading of a scale* or *noting the coincidence between two marks.*

In taking a reading one often finds that the pointer or the index of the instrument does not coincide with any of the division-marks of the scale, but lies in between two. Where accurate readings are neccessary, the fractional part of the division has to be taken into account. With a little practice one can acquire skill enough to read this fraction with an error not exceeding one-tenth of the division if the divisions are large. For small divisions you may estimate upto one-fifth or half a division. As an exercise you may try to estimate the fractional value of the part of the division to the left of the pointer in the diagrams of Fig. 1.1.(a). The actual values are given below the diagram.

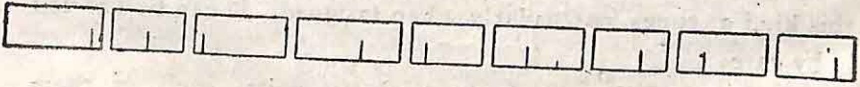

Fig. 1.1(*a*)

(The values from right to left are respectively, 0.8, 0.3, 0.7, 0.4, 0.2, 0.6, 0.1, 0.5, 0.9 of the division.)

If the divisions are smaller, your guess may not be as good as in the above case. Try Fig 1.1(b), choosing the rectangles at random.

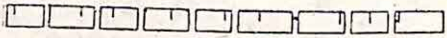

Fig. 1.1(*b*)

(The values from left to right are 0.2, 0.7, 0.3, 0.6, 0.3, 0.4 0.9, 0.5 and 0.1 of the division.)

1-2. Error. Any reading that you take involves some uncertainty, technically called an **error**. The term 'error' does not carry any sense of blame. It is only an 'uncertainty' and is inherent in all kinds of measurement.

Errors are due to various causes, some of which may be known and some unknown. A part is due to the personal judgment of the observer (which was employed, say, in estimating a coincidence between two marks or two occurrences, in determining the position of a pointer between two marks of a scale etc.). Besides, the instrument used for the measurement may have a defect, or slight changes in experimental conditions (such as small changes of temperature, pressure, voltage, humidity, etc.) may occur during the experiment. These and other factors contribute to the error.

Errors may be classified as follows :

I. Gross errors.
II. Systematic errors.
III. Random errors.

1-3. Gross errors. These include gross misreading of a scale, or the transposition of figures in recording the result. For example, 8·4 may be read as 9·4 or recorded as 4·8. We all make mistakes of this kind at times, particularly when fatigued. It can be avoided only by care.

Correction. When students work in pairs each of them should take the reading. This will serve as check against gross error by one. When working singly, the reading must be repeated, preferably thrice and at a different reading point where possible.

1·4. Systematic errors. If during an experiment a factor operates in such a way as to make the observed value always higher or always lower than the true value, the error it causes is said to be 'systematic'. A simple example is the 'zero error' of a reading instrument. All instrumental errors come under this head. The radiation loss or gain in calorimetric experiments, index correction in experiments with the optical bench are other examples of systematic error.

Systematic errors may be divided into three groups: (*i*) *instrumental*, (*ii*) *personal* (or *observational*) and (*iii*) *external* (or *environmental*).

1.41. **Instrumental errors**. All instruments and standards possess inaccuracies of some amount. Indicating instruments such as thermometers, ammeters, voltmeters, etc., generally have small errors of calibration, which are different in different parts of the scale. The actual value of a resistance may differ from the stated value by as much as 1% or even more, depending on the accuracy aimed at during manufacture. (Reputed manufacturers of instruments declare this error. It is known as 'guarantee error.') Unless these inaccuracies are known they cannot be taken into account. But the **zero errors** *of all scales should be carefully noted*, and the necessary correction applied to the reading.

1·4.2. Personal (or observational) errors. Two persons taking the same reading or making the same adjustment may not perfectly agree. One may have a tendency to read too high or too low, They may differ in timing an event or judging the level of intensity of a sound or light. Errors arising out of some peculiarity or bias on the part of the observer are known as *personal errors*. The most common source of personal error is the tendency to assume that the first reading is correct, and to look with suspicion at any variation from this reading. This *bias* must be avoided. *Whan taking a second reading, forget the first.*

Other personal errors may be due to fatigue, eye-strain or parallax.

1-4.3. External (or environmental) errors. These are errors due to changes in the conditions external to the measuring device. For example, all scales expand with rise of temperature, a wooden scale expands when the air is more humid, some instruments are affected by changes in barometric pressure, stray electric and magnetic fields, earth's magnetic field, etc.

Loss or gain of heat due to temperature difference in calorimetric measurements may be put in this class. It is systematic error due to *non-fulfilment of conditions* in which the relations hold.

1-4.4. Correction for systematic error. Where the source of systematic error is known, appropriate action is taken to eliminate it. Thus, the zero of a reading instrument is checked and the proper correction added to the reading. Error due to radiation loss is allowed to occur and then corrected for. Null points in electrical work are determined by reversing the current to reduce systematic error due to presence of small thermal e.m.f.

In some cases the source of systematic error may not be definitely known, but its existence be suspected In such cases the experiment is repeated *under altered conditions.* If variation of conditions produces no change in the result, one may set one's mind at rest regarding systematic error.

1-5. Random errors. Even after proper attention has been paid to all known sources of error, repeated measurements of the same quantity may show variations from reading to reading. There are undoubtedly reasons for these variations, but we are unable properly to account for them. Errors due to such variations are known as *random errors* (or *residual errors*).

Random errors are probably caused by a large number of small effects. Each one of them is variable and may by positive or negative. In some observations the positive and negative errors may be nearly equal, so that resultant error is small. In some cases, many of the errors may have the same sign (positive or negative), giving rise to a relatively large error.

Assuming that the individual small effects contribute *at random* to the resultant error, we may apply the laws of statistics to them to determine the best value and compute the error. To be staistically significant the number of readings should be large, at least 10. But as the student does not generally have the time for so many readings, his observations are limited to a smaller number, generally three, at most five. Estimate of random error based on such a small number is meaningless.

Correction for random errors. Since we do not have enough data, we cannot apply the statistical method for estimation of random errors. The best we can do is to *take as many readings of the same quantity as time permits, and use the mean.*

1-5.1 Deviation. The difference between any observational value (x) and the arithmetic mean (x_m) is called the *deviation* of x ($d=x-x_m$). When the measuring instrument is fine, as in the case of a screw gauge, different observations often give you the same value. The deviations, are practically zero. The random error in such a case is said to be **scale-limited.** This means that the random error is smaller than the smallest scale division.

In many cases the deviation is 1 small division or more.

Random error always affects the last digit of an observational value. It may affect even the previous digit.

1-6. Meanings of uncertainty, precision and accuracy of a measurement.

A. Uncertainty. When we say 'All measurements carry some uncertainty', we are using the word uncertainty in the same sense as error (§ 1-2). The statement carries to us the meaning, that any observed value of a quantity differs from the 'true' or standard value by *some* (unknown) amount. The term is sometimes used to mean the range or limits within which the 'true' value is *almost certain* to lie When a length is measured correct to the nearest millimetre and its value is found to be 43·2 cm, we know that the 'true' value most probably is somewhere between 43·15 cm and 43·25 cm. The uncertainty in this case may be taken as ±0·05 cm and the result expressed as 43·2±0·05 cm. 43·2 cm covers the range 43·15 to 43·25 cm.

Generally, the so-called "true" value is unknown and the magnitude of the error is hypothetical. Still, it is a useful concept for discussion.

B. **Precision**. By the term *precision* of a measurement is generally meant the degree of fineness with which it was made. Suppose that the length of a column of mercury is measured as 43·2 cm, no care being taken to measure it closer than the nearest millimetre. One way of stating the precision of the measurement will be to say that the measurement was made to the nearest millimetre. Another way to express the *precison* of the measurement is to state relative fractional or percentage error of the measured quantity (see Sec. 1-7). In the above example, the distance was not known closer than $\frac{1}{2}$ mm in 432 mm, *i.e.*, 1 part in 864, or $\frac{1}{864}\times 100$ $=0{\cdot}12\%$. This is the *relative uncertainty* or *relative error* of the measurement, and expresses its precision

A magnitude of high precision will have more significant figures (Sec. 1-9) in it.

C. **Accuracy**. The term 'accuracy' stands for the degree of closeness of the nominal or the observed value to the 'true' value or the 'standard' value. Of two one-ohm coils marked 1 ohm ±0·1% and 1 ohm ±0·5%, the former is the more accurate as it is closer to the standard value, ±0·1% and ±0·5% are the relative uncertainties of their values.

1-7. **Percentage error.** The importance of an error in an observed value is not in the *absolute value*, that is, the *numerical value* of the error, but in its value *relative* to the observed value.

$$\textit{Relative, fractional} \text{ or } \textit{Proportional error} = \frac{\text{absolute error}}{\text{observed value}}$$

$$\textit{Percentage error} = \frac{\text{absolute error}}{\text{observed value}} \times 100 = \textit{Relative error} \times 100$$

With one-degree thermometer you may not read a temperature with an uncertainty less than 0·2°. So if you get a rise of temperature of 4°, the percentage error is $(0{\cdot}2/4)\times100=5$. We may also say that the precision of the measurement is 5 in 100, or 1 in 20, or 5%.

In measuring a length with a metre scale, the error in the observation may be 1 mm. If the length measured is 61·2 cm, the percentage error is $(1/612)\times100=0{\cdot}16$. (Percentage errors need not be calculated beyond two places.) The precision here is 0·16 in 100 or 1 in 600. If the length measured were 2·324 metres, the percentage error would be 0·04 (*Precision* 0·04 in 100 or 1 in 2500).

Examples. (1)* The length of an index rod, read to the nearest millimetre with a metre stick is found to be 16·7 cm. What are the absolute and relative errors ?

Ans. Absolute error = ±0·05 cm. (Estimated value. See Sec. 1-8)

$$\text{Relative error}=\frac{0{\cdot}05}{16{\cdot}7}\times100=0{\cdot}3\%.$$

(2) A screw gauge can be read to 0·01 mm. What is the precision of the measurement of a distance of 2.5 mm.

Ans. Precision = 0.01 mm in 2·5 mm.

$$=1\text{ in }250=\frac{1}{250}=\frac{1\times100}{250}\%=0{\cdot}4\%.$$

(3) A resistance box claims to be accurate within 0.5%. What is the maximum absolute error when the nominal value is 2000 ohms ?

Ans. $\pm2000\times0{\cdot}5/100=\pm10$ ohms.

Note. We write errors with a ± sign, because an error may be positive as well as negative.

1-8 Errors in reading a scale by eye-estimation.

When a scale is read, there is generally an error in the eye-estimation of the fraction of the smallest scale division. This is primarily due to personal judgement of the observer and to parallax. The error of such an observation depends upon the fineness of the scale divisions of the instrument as well as on the skill and care with which the observation is made. Assuming that the instrument is correct, that reasonable care has been taken in carrying out the measurement, and that there has been no serious parallax error, we may reasonably expect that the error (uncertainty) of a *single reading* lies within the limits mentioned below.

Instrument	*Reading error*
Metre stick (graduated in mm)	0·5 mm
Slide callipers (Vernier const=0·1 mm)	0.05 mm
Screw gauge (least count=0·01 mm)	0·01 mm
Spherometer („ „)	0·02 mm
Physical balance (sensitivity 1 mg per small division)	2 mg
Thermometer (0·5°C div.)	0·2°C (using eye-estimation)
„ (0·1°C div.)	0·05°C („)
Stopwatch ($\frac{1}{5}$ sec.)	$\frac{2}{5}$ sec.

When *several readings* have been taken of the same quantity, we may take the **error of the mean**

(*i*) *as above*, when the deviations (Sec. 1-5.1) are smaller than the smallest scale division ;

(*ii*) *as the largest deviation*, when the deviations are 1 smallest scale division or greater. This may also be taken as *half the difference* of the extreme values.

Remark. Note that the above limits of error have been fixed somewhat *arbitrarily*. Such arbitrariness is inherent in all estimates of error. In all cases you are guided by your own judgement. This may differ somewhat from person to person.

This point should be remembered.

1-9 Significant figures. As we have seen, no physical measurement is ever *exact*. The precision is always limited by the refinement of the apparatus and the skill of the observer. In all readings the final digit is always *estimated*, and hence it is doubtful to some degree. Nevertheless, this doubtful digit is significant in a sense as it gives information about the quantity being measured. A *significant* figure (or *digit*) is defined as one that is known to be reasonably trustworthy. If a value is expressed in decimal notation, *there will be no sense in retaining a figure following the one that is estimated and hence is doubtful.*

Suppose that a metre scale, graduated in millimetres, gives the length of a rod as lying between 33·2 cm and 33·3 cm and that the fractional part of the millimetre is estimated as 0·6. The reading should then be shown as 33·26 cm. Any figure beyond the final 6 will have no sense; the 6 itself may be 4 or 8 depending upon the accuracy of the scale, the accuracy of the observer's eye-estimation, the parallax during the measurement, etc. The reading 33·26 has four significant figures. If the fraction of the millimetre were found to be zero, we should write the result as 33·20 cm. Here the zero is significant. If we omitted this zero, the value 33·2 cm would imply that the last digit 2 is doubtful. But according to the actual measurement there is no doubt about it. Hence by omitting to put the zero at the end we sacrifice our claim the precision with which we made the measurement. If a voltmeter capable of reading up to one-hundredth of a volt gives the value of the e.m.f. of a lead storage cell as 2·00 volts, the recorded value should include the two zeros. The recorded value should always express the degree of precision of the reading.

Though arithmetically 2 and 2·00 are the same it is *not so in physics.* The first has only one significant figure; the second has three such figures. Note that *the zeros we write to specify the position of the decimal point are not significant.* For example, we may write 2 as $0{\cdot}2\times10^1$, $0{\cdot}02\times10^2$, $0{\cdot}002\times10^3$. The zeros to the left of 2 are not significant as they merely determine the position of the decimal point. Here all the values have only one significant figure. But in 1·02 we have three significant figures.

1-10. Dropping of non-significant figures. In all kinds of calculation figures that are not significant should be dropped. This simplifies calculations, but does not lead to any loss of precision. It also prevents any claim to false precision.

In calculating a mean value, do not retain more significant figures than are contained in the individual values, Suppose the null-points in a metre-bridge experiment are found to be 52·1, and 52·4 on reversal of current. Recording the mean as 52·25 is improper, because the first decimal place in each reading is approximate. Hence the decimal figure in the calculated mean value, which does not have the necessary reliability, should be dropped,

When such non-significant figures are dropped, retain the last figure unchanged if the first figure dropped is smaller than 5. Increase the last figure by 1 if the first figure dropped is 5 or greater.

1-11. Significant figures in sums, products, etc. The following rules relating to Significant figures may be followed in addition, multiplication, etc.

1. In addition and subtraction, carry the operation up to the first column that contains a doubtful figure.

Example. Suppose we have to add 1·21, 12·8, 4·592 and 36·2 in all of which the last figure is doubtful. The sum should be expressed as 54·8. As the first decimal place in the second number is doubtful, the additon should not proceed beyond this figure.

Note that it is not necessary to determine the first and third numbers to the second and third decimal places for the purpose of this addition.

2. In multiplication and division, carry the operation to the same number of significant figures that are there in the factor with the least number of significant figure.

Examples. (*i*) Multiplying 4·592 by 36·2 we get arithmetically the value 166·2304. If the last digit of each number were doubtful, then the second number (36·2) has the least number of significant figures, which is three. Hence the product should be shown as 166, retaining only three significant figures in it.

Similarly in division.

(*ii*) Suppose the diameter of a wire is found as 2·37 mm in which the last digit is doubtful. It has been determined to three significant figures. Hence in computing its area we need not take more than three digits in the value of π. The cross-section, given by $3{\cdot}14 \times (2{\cdot}37)^2 \div 4$, *should be expressed with three significant figures as 4·41 sq. mm. It can also be written as 0·0441 sq. cm, without change of precision.

(*iii*) Consider the value of

$$\frac{1{\cdot}2 \times 36{\cdot}2 \times 546{\cdot}3}{4{\cdot}592 \times 2{\cdot}86}$$

in which the last digit of each number is doubtful. Using a four figure log table you will find the value as $1{\cdot}807 \times 10^3$. But the uncertainty in the last digit of the factor 1·2, which has only two significant figures, affects the second digit (8) of the calculated value and makes it doubtful. Hence the final value should be recorded as 1.8×10^3, retaining only two significant figures. Any additional figure will have no significance, and should not be included.

1-12. Calculation of final result. From what we have seen above it is clear that

The precision of the final result is not higher than that of the quantity which was determined with the lowest precision.

Hence there is no sense in using five or seven figure logarithmic tables for calculation unless all data carry as many significant figures. In many of the quantities you measure (particularly in temprature) you hardly attain a precision of 1 in 100. Hence any final value which is directly dependent on this quantity need not be calculated beyond three significant figures. Retention of all the four figures in a result obtained by calculation with a four-figure log table is justified only when all the quantities involved in the experiment have been measured with a precision of 1 part in 1000. This is rarely achieved in ordinary class experiments.

Accumulation of rounding off errors. Note that the rounding off of the last digit causes a small error. Accumulation of rounding off errors may exceed the experimental uncertainty. In extended calculations it is therefore necessary to guard against such rounding off errors. For this reason it is safer to work through a long calculation using one more figure than are indicated to be significant by the precision of the original observations. But in the final result only the requisite number of significant figures should be retained.

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*The constant numeral 4 in this expression should be considered to have an infinite number of significant figures following it, which are all zero.

In rounding off, if the dropped figure is 5, leave the preceding figure unchanged if it is even; but increase it by 1 if it is odd. In rounding off 52·25, we therefore take it as 52·2. But to round off 52·15, we write 52·2

1-13. Precision needed in a measurement.

The questions which concern us most are generally the following:

1. How to estimate the error in the value of a single quantity. (This has been answered in Sec. 1-8)

2. To what precision should we push the measurement of a quantity when we have several quantities to measure for the experiment. (For answer see Sec. 1·13.1)

3. How to estimate the error in the final result (Sec.-s 1-14 and 1-15.1)

1-13.1. Planning an experiment.

This section gives the answer to enquiry 2 of the last section (Sec. 1-13).

Let us suppose that a quantity f is related to several other quantities $x, y, z, \ldots\ldots$ by the relation $f = k\, x^a y^b z^c \ldots\ldots$ where k is a constant.

Let $\delta f, \delta x, \delta y, \delta z$, etc. represent the absolute errors in the observed quantities. It may be shown by simple calculation that the *maximum value* of $\delta f/f$ is given by

$$\left(\frac{\delta f}{f}\right)_{max} = a\frac{\delta x}{x} + b\frac{\delta y}{y} + c\frac{\delta z}{z} + \ldots\ldots \qquad (1\text{-}13.1)$$

In this equation a, b, c denote only the *numerical values* of the powers and are to be taken as positive.

Now, $\delta f/f$, $\delta x/x$, etc. are the *fractional* (*proportional* or *relative*) *errors* in the measurement of the respective quantities. Each multiplied by 100 is the corresponding *percentage error*. The actual error in f may be less than that given by Eq. 1-13.1 as the errors in the individual quantities may not conspire to act all in the same direction. (See Sec. 1-14)

Since the relative error in each quantity of a product or quotient is multiplied by the corresponding power in the final expression for the maximum error, it follows that the quantity having the highest power should be measured with a higher precision than the rest.

Examples. (1) To illustrate what we mean, let us take the case of the determination of Young's modulus (E) by stretching.

Let the data be as follows ;

Stretching load (w) $=1$ kg,
Length of wire (l) $=150$ cm,
Radius of wire (r) $=0{\cdot}35$ mm,
Elongation (e) $=0{\cdot}32$ mm.

The formula connecting the quantities is $E=\dfrac{wgl}{\pi r^2 e}$.

The power is 2 for r and 1 for all other quantities. If we can measure both e and r with an error not exceeding 0·01 mm, the proportional error in r will be $\delta r/r=1/35=3\%$ (nearly). Its contribution to the maximum error in E will be twice this value, *i.e.*, 6%. This shows that r has to be determined with a higher precision than e. *The proportional error of r should be half that of e.* So we should take a larger number of readings of r *unless the error is scale-limited* (Sec. 1-5.1).

Note that even if we make an error of 1 cm in the determination of l, the contribution of this to the error in E will be only $\dfrac{1}{250}\times 100=0{\cdot}4\%$, a value much less than that due to r or e.

(2) Let us take another example—the determination of the specific heat of a solid by the method of mixtures. Consider the following data, condensed for convenience.

Heat capacity of calorimeter with contents (w) $=64{\cdot}84$ cal/°C,
Initial temperature of calorimeter (t_1) $=29{\cdot}5$°C,
Final „ „ „ (t) $=34{\cdot}5$°C,
Initial „ „ heated body (t_2) $=97{\cdot}5$°C,
Mass of the solid (m) $=23{\cdot}19$ g

The formula for specific heat s is

$$s=\frac{w(t-t_1)}{m(t_2-t)}=\frac{w\theta}{m\theta'},$$

θ representing the temperature-rise of the calorimeter and θ' the temperature-fall of the solid. All quantities on the right-hand side of the equation occur in the first power.

Suppose the temperatures are determined with an uncertainty of 0·1°C. t_1 may be 0·1°C too high while t may be as much too low. Hence the error in θ may be 0·2°C. The percentage error in θ may then be $\frac{0{\cdot}2}{5}\times 100=4$. The percentage error in θ' is less; it is $=\frac{0{\cdot}2}{63}\times 100=0{\cdot}3$ nearly. Even if the masses are determined with an uncertainty not better than 0·1 g, the contribution of this to the final error is 0·4% nearly.

Thus we find that in this experiment the main contribution to the final error occurs through the uncertainty in θ, the temperature-rise. Attempt should be made to reduce this error to the minimum value possible under the circumstances. This can be done (*i*) by using a tenth-degree thermometer (*i. e.*, reading directly up to 0·1°C) and (*ii*) arranging that θ is large, which can be secured by reducing the value of w and increasing the value of m. The accuracy in the measurement of the mass of the calorimeter and its contents need not be pushed higher than 0·1g, because the error due to it, as we have already seen, is much smaller than that in θ.

Summary. In consideration of the above, it is appropriate that we adopt the following as our guide :

The measurement of different quantities in an experiment should be so planned that the relative error of each contributes nearly the same amount to the total error in the final result. This means that the terms occurring on the right hand side of Eq. 1-13.1 should be nearly the same in value. If one term is much larger than the rest due either to the presence of a power higher than unity or due to the proportional error itself being large, special care should be taken to reduce it. *Relative error can be reduced by*

(*i*) *using a measuring instrument capable of a higher precision,*

(*ii*) *where possible, increasing the value of the quantity to be measured, and*

(*iii*) *repeating the readings.*

1-13.2. Propagation of errors. Note here that

(**A**) The *numerical* or *absolute error* of a sum or difference is **the sum** of the *numerical errors* of the individual quantities.

[*Ex* : If $f=u+v$, then $\delta f=\delta u+\delta v$.]

(**B**) The *percentage* (or *relative error* of the product or quotient of several numbers is the **sum** of the *percentage* (or *relative*) *errors* of the several quantities entering into the calculation.

(C) When the final result depends on *some power* of a quantity, the contribution of the relative error of the latter to that of the former is *power times the relative error* (power × relative error).

1-14. Maximum and Probable error in the final result. In most laboratory work the value of the quantity to be determined generally depends on the values of several other quantities. Each of the quantities involves some error. The question naturally arises, 'What is the error in the final result ?' Eq. 1-13.1 gives the *maximum* (*relative*) *error* in the final result ; the actual error may be less.

Let us assume that a quantity f depends upon two other quantities x and y, and that e_x and e_y are the *relative errors in x and y respectively*. The error in f may not be e_x+e_y, for this would imply that when a deviation in x is positive, that in y also is positive. If the deviations of x and y are independent, the resulting *probable* (*relative*) *error* e_f in f is given by

$$e_f=\sqrt{e_x{}^2+e_y{}^2}. \tag{1-14.1}$$

This relation states how errors are propagated and applies to any number of quantities, provided their *deviations are independent.*

Note that if $f=kx^a y^b z^c\cdots$ (Sec. 1-13), then the error δf_x in f due to an error δx in x is given by

$$\delta f_x=\left(\frac{\partial f}{\partial x}\right)\delta x,\ \text{or}\ \frac{\delta f_x}{f}=\left(\frac{\partial f}{\partial x}\right)\frac{\delta x}{f}=a\,\frac{\delta x}{x}. \tag{1-14.2}$$

Similarly, $\delta f_y=\left(\frac{\partial f}{\partial y}\right)\delta y,\ \delta f_z=\left(\frac{\partial f}{\partial z}\right)\delta z$, etc.

When δx, δy, δz, etc. are independent then the final error in f is given by

$$\begin{aligned}\delta f&=\sqrt{(\delta f_x)^2+(\delta f_y\ {}^2+(\delta f_z)+\cdots}\\&=\sqrt{\left(\frac{\partial f}{\partial x}\right)^2\delta x^2+\left(\frac{\partial f}{\partial y}\right)^2\delta y^2+\cdots}\end{aligned} \tag{1-14.3}$$

$$\text{or,}\quad \frac{\delta f}{f}=\sqrt{a^2\left(\frac{\delta x}{x}\right)^2+b^2\left(\frac{\delta y}{y}\right)^2+\cdots} \tag{1-14.4}$$

The working of this formula has been well illustrated in Sec. 3-2.1. A simple example is discussed below,

Example. In an experiment with the simple pendulum, the length, 80'0 cm, was read with an uncrertainty of ±2 mm, and the time for 25 oscillations, 45'0 seconds, with an uncertainty $\pm\frac{2}{5}$ s. What is the maximum error in the value of g calculated from the data ?

Ans. Relative error in $l = \frac{\delta l}{l} = \frac{2\text{mm}}{80\text{ cm}} = \frac{1}{400} = 0{\cdot}0025$. Relative error in $T = \frac{\delta T}{T} = \frac{2}{5}/45 = \frac{2}{225} = 0{\cdot}0089$. Since $g = 4\pi^2 \frac{l}{T^2}$, we shall have

$$\delta g_l = \pm 4\pi^2 \left(\frac{\delta l}{T^2}\right) \text{ and } \delta g_T = \pm 4\pi^2 \frac{2l}{T^3}\,\delta T.$$

The maximum relative error $\frac{\delta g}{g} = \pm \frac{\delta g_l + \delta g T}{g}$

$$= \pm \frac{4\pi^2\{(\delta l/T^2) \pm 2l\delta T/T^2\}}{4\pi^2 l/T^2} = \pm\left(\frac{\delta l}{l} + 2\,\frac{\delta T}{T}\right)$$

$$= \pm(0{\cdot}0025 + 2\times 0{\cdot}0089) = \pm 0{\cdot}0203 (i.e.\ 2{\cdot}0\%)$$

g(as from the observed data) $= 4\pi^2 \times 80/(1{\cdot}8)^2 = 975$.

Hence maximum absolute error $= \pm 0{\cdot}0203 \times 975$ (approximately)

$= \pm 19{\cdot}8$.

Result $= 975 \pm 20$ cm/s^2.

Note that the data, as given, do not ascribe significance beyond the third digit.

The above data were obtained by a beginning student in the laboratory. In the assessment of uncertainty he was assisted by the instructor. The student was distressed by the calculated value of g and the limit of error. His distress arises out of the familiar misconception among students that they are in the laboratory to reproduce the known values of the experimental quantitites. *This misconception should be removed* at an early stage, and he should be encouraged to estimate the uncertainty of the result, and make efforts to reduce this uncertainty

The student may seek some consolation by using fomula 1-14.4 for calculating the relative error. This value comes out to be $\{(0{\cdot}0025)^2 + (2\times 0{\cdot}0089)^2\}^{\frac{1}{2}} = 0{\cdot}018$. This reduces the absolute error to $\pm 975 \times 0{\cdot}018 = \pm 18$ in place of ±20. So the consolation is poor. It is so because the relative error in T is about *seven times* that in l. A well planned experiment tries to make all the relative errors about equal, as was pointed out in Sec. 1-13.1.

1-15. Things to remember. Each measurement involves some uncertainty, called *error*. An error may be (*i*) gross, (*ii*) systematic, or (*iii*) random (§ 1-3 to § 1-5).

Proportional or *relative error* is the value of the absolute (or numerical) error expressed as a fraction of the value of the quantity. If this fraction is expressed as a percentage, it is called the *percentage error*.

The 'precision' (§ 1-6) of a measurement is expressed by the relative error.

'Accuracy' (§ 1-6) represents the degree of closeness to the standard value.

The maximum relative error in the final result is the sum of the component relative errors (§ 1-13.1)

An experiment should be so planned that the relative errors in all the quantities are about equal.

The last figure in the value of a directly measured quantity is estimated, and hence is doubtful. Any figure beyond this one is non-significant. Numerical calculations should not be carried beyond the first digit affected by a non-significant figure (§ 1-9 to 1-11).

1-15.1. How to calculate the error in a result.

(*i*) Measure all the quantities concerned and use the mean of each for calculation.

(*ii*) Estimate the absolute error in each. For this purpose, you may use the table in Sec. **1-8**, when the readings are *scale-limited* that is, identical (Sec. 1-5.1), or use the largest deviation or half the difference of the extreme values (Sec. 1-8).

(*iii*) Calculate the relative (or percentage) error of each quantity. (A percentage error need not be calculated to more than two figures.)

(*iv*) If any of the quantities occur in a power (positive or negative) other than unity, multiply its relative error by the power. This is the contribution of the relative error of this quantity to the relative error of the final result.

(*v*) Apply Eq. 1-13.1 or 1-14.4 according as you want the maximum error or a probable error.

(*vi*) Remember that if a quantity is the *sum or difference* of two quantities, the maximum error in the quantity is the *sum* of the absolute errors of the two quantities.

1-16. Graphs. Experimental observations are often expressed in the form of graphs. When the value of any quantity depends on another, one of them is allowed to vary at will, generally in convenient equal steps, and the corresponding value of the other quantity is observed. The corresponding values of the two quantities are then plotted on a squared paper.

In plotting the points and drawing the graph, attention should be paid to the following :

(*i*) The quantity which has been allowed to vary at will is ordinarily plotted along the horizontal axis (called the *abscissa*) and the other along the vertical axis (called the *ordinate*). The quantity plotted along an axis should be noted by the side of the axis.

(*ii*) The unit along each axis should be chosen with a view to utilising the larger part of the graph paper, and at the same time retaining convenience of plotting **The unit of length on the graph paper and the unit of the quantity to be plotted shoul bear to each other a simple ratio.**

(The student is often told to utilise the whole of the graph paper at his disposal. Unintelligent adherence to this advice more often leads to difficulties of plotting Suppose that along the horizontal axis he has altogether 85 divisions, while the total change in the value of the quantity he wants to plot along that axis is 52. Should he take each division to represent 52/85 unit ? The answer is an emphatic 'No'. A little inspection of the quantities would show that plotting is much simplified if 3 divisions represent a change of 2 units. This utilises 78 divisions out of the 85 available.)

(*iii*) After the unit has been chosen, the value of the quantity (to be plotted) corresponding to each (or every alternate) large division mark (i.e., those corresponding to the thicker lines, which are 1″, $\frac{1}{2}$″ or 1 cm apart) should be noted down on the squared paper. This should be done for both axes. The values so marked should be integers, tenths or hundredths, but never *bad fractions.*

(*iv*) The experimental values are then plotted. Each point should be marked by a small dot surrounded by a light circle, or a cross. The coordinates of a point need not be noted by its side unless it is required for quick reference. Much writing near the graph gives it an ugly look.

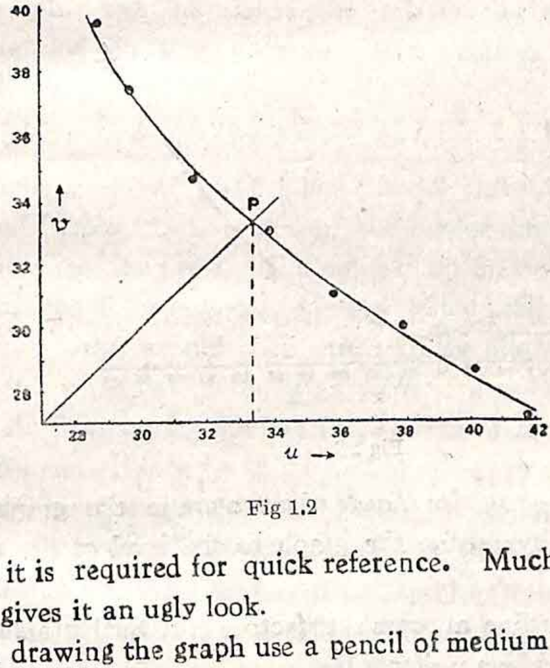

Fig 1.2

(*v*) In drawing the graph use a pencil of medium hardness and an eraser of good quality.

(*vi*) The points plotted may not appear to lie on a straight line or a curve.

(*a*) **When the graph is known to be a straight line passing through the origin, the best straight line is the one passing through the origin (0, 0) and the point $(\bar{x}, \bar{y})$ defined by the mean values of the x's and y's. (This procedure is justified by the method of least squares in Statistics or the theory of errors.)**

(*b*) When the graph is known to be a straight line, but no single line could be drawn so as to pass through all the points, a simple course is to draw a straight line such that the *sum of the vertical distances of points lying above the line is equal to that below it.** Points lying far off the graph may be rejected.

The same procedure should be followed when the graph is a curve. In drawing the curve a trial outline may be lightly marked by broken lines and then the necessary alterations made in it

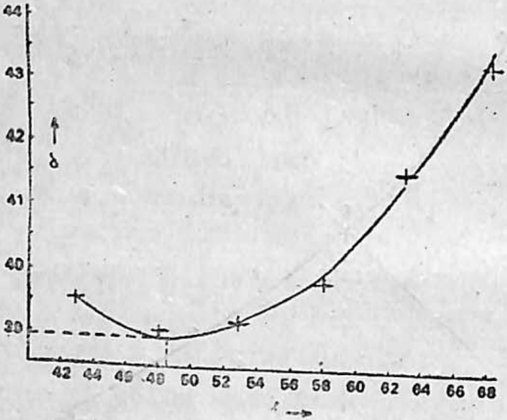

Fig 1 3

There should be *no sudden change of curvature* in the graph. This may be tested by raising the graph to the level of the eye and inspecting.

When the outline appears satisfactory the final graph may be drawn. It should be a uniform line.

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*The best course is to follow the *method of least squares.* It states that the sum of the squares of the vertical distances of experimental points from the straight line should be a minimum.

Let $y=mx+b$ be the equation to the straight line. Suppose n readings of x and y have been taken. Denoting a corresponding pair of readings by x_i and y_i where i will have values from 1 to n, the method of least squares gives the following values of m and b :

$$m=\frac{n\Sigma(x_i y_i)-\Sigma x_i \Sigma y_i}{n\Sigma x_i{}^2-(\Sigma x_i)^2} \tag{1 16.1}$$

$$b=\frac{\Sigma x_i{}^2\Sigma y_i-\Sigma x_i \Sigma(x_i y_i}{n\Sigma x_i{}^2-(\Sigma x_i)^2}, \tag{1.16.2}$$

(*vii*) If any value is found out from the graph, the corresponding ordinates should be marked by dotted lines. The point on the graph should also be marked.

The above points are illustrated by means of two graphs (Figs. 1.2 and 1.3) the data for which were taken from a student's laboratory note-book.

u v graph. Fig. 1.2 shows the relation between the object distance (u) and the image distance (v) of a convex lens. The data are as follows :

u (in cm)	28.7	29.7	31.7	33.7	35.7	37.7	39.7	41.7
v (in cm)	39.5	37.6	34.9	33.1	31.2	30.1	28.7	27.7

To find f from the $u—v$ graph, the scales for u and v on the graph must be the same. The point (0,0) may or may not be on the graph, but it is necessary to draw a line inclined 45° to either axis, which line should pass through the above point. This is satisfied if a point having the same value of u and v is taken as the origin. At P where the 45° line through the origin cuts the graph, $u=v=33{\cdot}4$ cm. Hence $f=16{\cdot}7$ cm.

i-δ graph. Fig 1.3 shows the relation between the angle of incidence (i) and the angle of deviation (δ) in the case of a prism. The measurements were made with a spectometer by a student during his class-work. The data are as follows :

i	43°	48°	53°	58°	63°	68°
δ	39°30′	39°3′	39°13′	39°53′	41°35′	43°21′

The graph paper available was of 15 cm × 12 cm ruled area. Each centimetre along the horizontal axis was taken to represent 2°, i being plotted along it. Along the vertical axis, which represented δ, each centimetre was taken as 30′ (*i, e.* 1 mm or each small square = 3′).

From the graph it was required to find the smallest value of δ and the corresponding value of i. These are marked by dotted lines. The values were $\delta = 38°57'$ and $i = 48°48'$.

Skill in drwing graphs can be acquired by practice only. The student is advised to draw graphs from his own data wherever

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possible. This will not only give him skill, but also help him in realising the precision of his measurements.

1-17. How to record data. The recording of data in class experiments hardly receives from the student the attention it deserves. It should be done as follows :

(i) **Record all data that you observe.**

(ii) **Record them in the order that you observe them.**

(iii) **Provide appropriate headings indicating the quantity to which a particular series of data refers.**

(iv) **Mention the units**

The *precautions* taken should be indicated at the end of this record, or put down at the right place while making the record.

The *calculations* made to arrive at the final result must be shown. This may be done on the left-hand page of the laboratory note-book. Log tables should be used for calculations.

The *final result*, expressed in the correct unit *retaining the proper number of significant digits*, should be clearly marked.

The above method of recording data has been illustrated in in most of the experiments described in this book. When data are recorded in the above way it becomes *unnecessary* for *the student to write an account* of what he did (the so-called 'Procedure') in carrying out the experiment ; but he should mention the principal adjustments he makes. A *model* for such writing has been given almost in every experiment.

More emphasis should be laid on multiplication of data, and less on descriptions. *Maximum error* in the final result should be calculated and expressed as a percentage.

1-18 Things to remember. The student will find it useful to remember the following :—

(1) *Take several readings of the same quantity under unaltered conditions in order to eliminate gross errors and to reduce random errors in the measurement.*

(2) *Repeat the experiment under suitably altered conditions in order to detect any systematic error that may be present.*

(3) *The precision in the measurement of different quantities should be so arranged that the contribution to the maximum error due to each is nearly the same.*

(4) *The final result should not be so calculated as to imply a precision higher than that in the quantity having the least precision of measurement* (that is, it **must not contain non-significant figures.**)

(5) *Record all data that you take and in the order that you take them. Provide suitable headings to indicate the quantity to wihich the data refer.*

(6) *At the end of the experiment, give a very short account of the method you have followed.*

1-19 General Instructions

1. **Preparation for the experiment.** (*i*) Read through the experiment carefully, trying to understand it. Make a mental note of the successive steps you should take in carrying out the work.

(*ii*) Reach the laboratory in time, equipped with a pen, a sharpened pencil of medium softness, a ruler (preferably transparent) with cetimetre divisions, and a pencil eraser of good quality.

2. **Performing the experiment.** (*i*) Make sure that you have all the apparatus you require.

(*ii*) Be neat and methodical in your work.

(*iii*) Record the data in ink or soft pencil in the final form. *Do not copy it again* ; this may lead to error or arouse suspicion that the data have been tampered with.

(*iv*) *If a mistake has been made in recording a datum, cancel the wrong value by drawing a line through it, but keeping it legible.*

(*v*) The data should be recorded in tabular form with appropriate heading and mention of units. (Tabular forms to record data have been given in the book to serve as guide.) These records should be so clear and complete that another person may not have any difficulty in understanding them without reference to you.

(*vi*) At the end of the work disengage the apparatus and leave the components as you found them.

3. **Writing up the experiment.** Treat this also as an essential part of the experiment. Be neat and Methodical in writing up. The following method of recording the experiment is suggested.

Heading. Write the title of the experiment in *block capital letters* and underline it. Don't waste time in ornamentation.

Diagram.* Draw line diagrams in pencil to illustrate the assembed apparatus, and *lable the parts*. (Shading to illustrate depth is unnecessary; a two-dimensional figure illustrating the essential parts is generally enough.)

In electrical work, only a circuit diagram is necessary.

Theory. Include an outline of the theory underlying the experiment. Where there is a working formula, it will do to state the conditions in which it holds, write the formula and clearly explain the symbols used. No deduction of the formula is necessary.

Apparatus. Give a complete list of apparatus used. No description of any apparatus or of its mode of action is necessary. (In this book these have been provided at places to enable the student intelligently to handle the apparatus. The student must have through familiarity with the apparatus.)

Experimental data. For recording data, see items (*iii*) to (*v*) under the heading 'Performing the experiment' earlier in this section. Be sensible about the degree of precision with which you record data (*see* Sec 1·9, 1·10 and 1·11).

Calculation. The mean values of the observed data should be entered in the tables. Where the calculation of the final result requires use of logarithmic tables, it should be shown neatly and fully on the left-hand page of the laboratory note-book. Don't hide

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*A *diagram* is a representation in lines which shows the essential features of the object. Correct proportions are not insisted upon.

A *sketch* is a representation in outline showing correct proportions.

A *picture* is a representation of what the object looks like. This requires shading to represent the third dimension.

the calculations in a back page in an examination ; *these are an essential part* of your work and subject to inspection.

Result. Always put the units in the final result and record it clearly.

Method followed. This need be only a short statemet of what you have done successively. Elaboration is not necessary as the steps you have followed can be easily understood from your recorded dita. (Models of such writing have been given in the book.)

Precaution. Briefly mention any special precautions you might have taken .

Instructions on how to proceed with the experiment have been given in the book under the heading **Instructions** placed immediately after the list of apparatus.

Revision questions

1. Explain what is meant by the following terms : Error ; significant figure, gross error, systematic error, randem error, absolute error, relative error, percentage error.

2. State the rules for the proper number of significant figures to be retained in addition, in subtraction, in multiplication, in division. Give an example of each.

3. Which of these specifies the precision of a measurement—absolute error or relative error ?

4. How are errors propagated in addition, in subtraction, in multiplication, in division ? Give an example of each.

5. How would you plan an experiment to minimize the error in the final result ?

Problems

1. Which of these are systematic errors :

(*a*) Displaced zero of a scale ; (*b*) parallax ; (*c*) friction of a moving pointer ; (*d*) error in eye-estimation ; (*e*) lack of uniformity in the quantity to be measured (say, diameter of a wire) ; (*f*) change of temperature during work ; (*g*) index error ?

2. In some of the cases mentioned in Problem 1 the error may be systematic or random depending on circumstances. Pick out such cases and state the circumstances in which the error may be random.

3. A metre stick is used to read a length of (*a*) 6 cm, (*b*) 20 cm, and (*c*) 60 cm to the nerest millimetre. Assuming that the uncertainty in an observation of this kind is 0·5 mm, calculate the relative and percentage errors in the three cases.

4. A travelling microscope can be read to 0·1 mm. What are the relative and percentage errors in a measurement of 1 cm ?

5. A metre stick can be read to the nearest millimetre. If the error is not

to exceed 1%, what is the smallest distance in measuring which the metre stick can be used ?

6. An ammeter reading 0—5 amp. has 50 equal divisions. If the uncertainty in an eye-estimation is one-fifth of a division, what is the precision of measurement at (*a*) 1 amp, (*b*) full scale ?

(Precision of a measurement is expressed by stating the relative or the percentage error.)

7. A stop-watch is graduated in one-fifth seconds. What is the minimum time interval that can be measured with a precision of 0·1 per cent ?

8. A stop-watch loses 5 seconds in 30 minutes. What total and percentage errors are made in measuring a time interval of 2 min. 30 sec. with it ?

9. A body weighs 51·38 g in air and 30·76 g in water. If the uncertainty of an weighing is 10 mg what is the maximum error in the value of the density ?

[*Hint* ; The maximum absolute error in the volume will be ± 0·02 cm^3]

10. In a metre-bridge measurement of resistance the null point is at 55·3 cm. The uncertainty in the null point is 1 mm. The known resistance is 5% accurate. What is the inaccuracy in the value of R if $R=[55·3/(100-55·3)]\times 10$ ohms ?

11. If the relative error in the final result is 1% and a four figure log table is used for calculation, should the result be left with four figures ?

12. In a determination of specific heat by the method of maxtures the temperature rise was 8°C. The estimated error in the reading was 0·2°C. If the hot body dropped into the calorimeter had a mass of about 100g, should it have been weighed to the nearest (*a*) gram, (*b*) decigram, (*c*) centigram or (*d*) milligram ?

[Ans. Nearest gram.]

13. The amount of water in a calorimeter is 100g. The mass of calorimeter is about 150 g and the specific heat of its material is 0·1 cal/g°C. Is it necessary to weigh the calorimeter beyond the nearest gram ? [Ans : No.]

14. In an experiment on the determination of Young's modulus (E) by stretching, the diameter of the wire was found to be 0·82 ± 0·02 mm. If E depends on the square of the diameter, what percentage error in its value does the uncertainty in diameter contribute ?

If the wire has length of about 2·5 metres and is measured to the nearest centimetre, what error does this uncertainty introduce in the value of E ?

15. The focal length of a thin lens is measured, using the relation

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}.$$

u is found to be 24·3 ± 0·05 cm, v is 17·4 ± 0·05 cm. What is the precision of the f measurement ?

[*Hint* : Differentiate and write $\frac{\delta u}{u^2}+\frac{\delta v}{v^2}=\frac{\delta f}{f^2}$. Put $\delta u=0·05$, $\delta v=0·05$, $u=24·3$ and $v=17·4$. Calculate δf. This is nearly 0·025. Calculate f from the first relation $f=10·1$. Precision = 0·25%].

CHAPTER 2 : MEASUREMENT OF LENGTH AND MASS

2-1. The metre scale. In measuring a length you may be called upon to use a scale, such as the *metre scale*, which is graduated in centimetres and millimetres. Or, it may be a foot rule in which the divisions are in inches and fractions thereof.

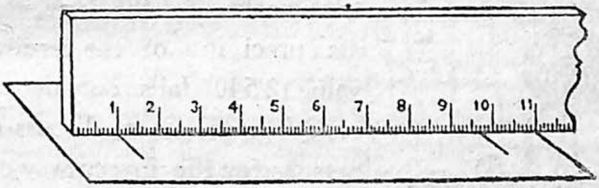


Fig. 2.1

In using a scale, first make sure of the unit (inch or centimetre) in which it is graduated, and also the value of the smallest scale division. Take the following *precautions* :

(*i*) Place the ruler on its side (Fig. 2.1) so as to bring the division marks of the scale as close as possible to the points the distance between which you want to measure.

(*ii*) In taking a reading avoid parallax (Fig. 2.2 ; E_2 is the correct position of the eye).

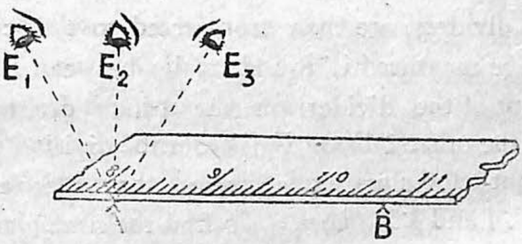


Fig. 2.2

(*iii*) Measure the distance by *difference*, as illustrated in Fig. 2.1. Do not use the zero end of the scale as it may have been damaged or worn out.

When it is inconvenient to place a scale close enough to a body, you may use a pair of dividers (Fig. 2.3). The dividers are set to the length to be measured and transferred to the scale. Dividers provided with screws (Fig. 2.3) are more convenient to use.

Find from your data the number of centimetres to the inch, and calculate the precision of the result. If the true value (2·540) falls outside the limits of experimental error, discuss the probable reasons for the inaccuracy of your result.

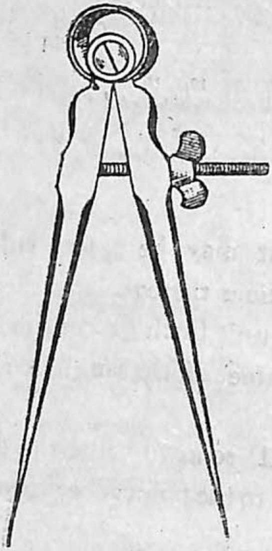


Fig. 2.3

2-2. The diagonal scale. The diagonal scale may be graduated in inches or centimetres and is capable of measuring a length up to 0·01 inch or 0·01 cm. It is divided into ten equal spaces parallel to its length (Fig. 2.4). The right-hand division (inch or centimetre) is also subdivided by ten equidistant *diogonal lines.*

To measure the distance between two points by a diagonal scale, we take a pair of dividers and open them so as to make their ends agree with the points. The dividers are then transferred to the scale. Suppose the length to be measured is found to lie between 1 and 2 inches. Place one point of the divider on the 1-inch division (at *E*) and suppose that the other falls on *F*. From the division marks on the top of the right-hand square one can see that the required length lies between 1·4 and 1·5 inches. To find the next place of decimal, move the divider across the scale downwards and parallel to itself, one end always remaining on the vertical line through *E*. The other end will describe the dotted line as drawn in the figure through *F*. This line cuts only one of the diagonal lines (in this case the fourth) at the point where that is also cut by the horizontal line sixth from the top. It may be readily seen from this that the length *EF* is 1·46 inches. The first decimal place is obtained from the figures at the top of the right-hand square and the second decimal place from those to its right.

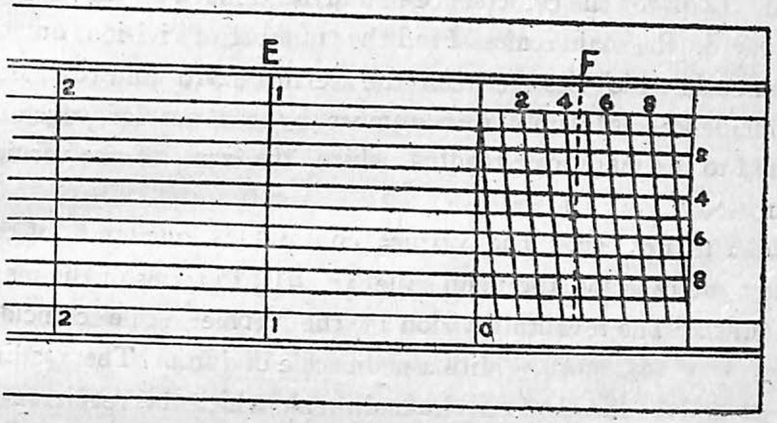


Fig. 2.4

Note that the zero of the scale starts from the left of the divided square.

2·3. The vernier. The *vernier* is an auxiliary scale which is used along with a common scale, called the *main scale*, for measuring fractions of the smallest division of the main scale.

How to use a vernier. For reading verniers correctly the following steps are recommended :

(*i*) Find the value of the smallest division on the main scale.

(*ii*) Place the zero mark of the vernier scale against one of the long division marks of the main scale. As you look up the vernier scale you will find that some other division mark on it (at the other end) coincides with another division mark on the main scale. Find the number of the smallest divisions of the main scale, as also the number of vernier divisions, which lie between these coincident division marks. The correspondence is generally of 9 of the former to 10 of the latter, or of 19 to 20, 24 to 25, or 49 to 50. Calculate the vernier constant, which is generally 1 scale division —1 vernier division. Express the value in a suitable unit.

(*iii*) Place the zero end of the vernier in contact with the extremity of the object whose position on the scale is to be determined. Look for the coincidence of a division mark on the vernier with one on the main scale. Find the number of divisions on the vernier scale which lies between the vernier zero and the mark of coincidence. Multiply this number by the vernier constant and add to the main scale reading which the zero of the vernier has crossed.

Refer to Fig. 2.5. The vernier constant is one-tenth of the smallest division of the main scale (*i.e.*, 0·01 in terms of the main scale unit). The seventh division of the vernier scale coincides with a main scale division. The reading on the main scale which the vernier zero has crossed is 5·3. Hence the reading provided by the vernier is 5·3+7×0·01 =5·37 in the appropriate unit.

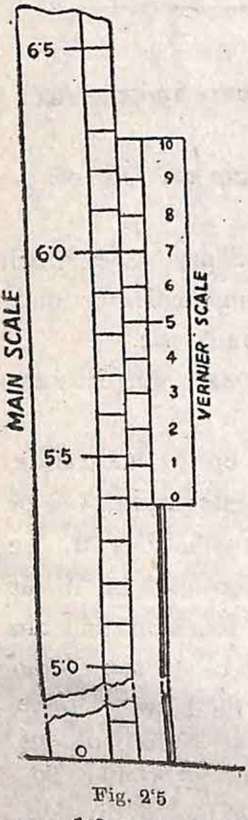


Fig. 2·5

Special verniers. In some *barometers* the vernier provided with the centimetre scale has 10 divisions of the vernier corresponding to 19 millimetre divisions of the main scale. The student is often confused by this departure from his ordinary experience. The difficulty may be obviated if he takes the vernier constant in the case to be

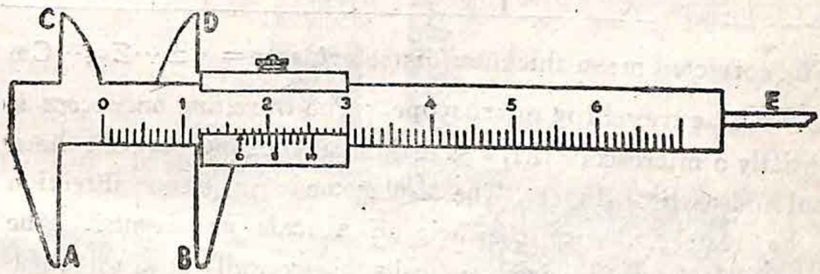
2 scale divisions—1 vernier division.

The reason for so doing is not difficult to find. Following the principle of the vernier he can easily see that if the first vernier division mark coincides with a main scale division the additional distance which the vernier zero has crossed is 2 mm−1·9 mm=0·1 mm. In using such a vernier the rest of the procedure will be the same as already described.

The *advantage* of a 19, 10 agreement over the more usual 9, 10 agreement lies in the wider spacing of the vernier divisions which makes it easier to read and reduces strain in the eyes.

Verniers are also used with *circular scales* for reading the value of an angle accurately as in a spectrometer. Note that in circular scales the divisions are in degrees and minutes of arc, and not in centimetres or millimetres.

2.4. Vernier slide callipers. The instrument is an application of the principle of the vernier described above. It (Fig. 2.6) has two jaws, *AB* and *CD*. The body whose length has to be measured is held between the jaws *AB*. The jaws *CD* are used to measure the inside diameter of a tube or hole, and the tail *E* (where there is one) for depth. If the instrument is not defective, the zero of the vernier should coincide with the zero of the main scale when the jaws *AB* are in contact. If the two zeros do not agree, there is a *zero error*. Always examine your instrument for zero error before you use it. See whether the zero of the movable scale is to the right or left of the zero of the fixed scale and find by how much. If to the right, the zero error is to be subtracted from the final reading. If it is to the left, it should be added. Then find the vernier constant as follows :



Fig, 2,6

… vernier divisions = … main Scale divisions
∴ 1 ,, ,, = … ,, ,, ,,
Smallest Scale division = … mm = … cm
∴ Vernier constant (V. C.) = 1 scale div.—1 Vernier div
= … cm

Now to measure the (i) thickness of a wooden block, hold the block lightly between the jaws *AB*, (ii) inner diameter of a metal washer, insert the jaws *CD* into the opening to touch the sides lightly, (iii) depth of a hole, insert the tail *E* into the hole such that the end of the main scale rests on the top of the hole. Take the readings as follows :

Vernier constant=···cm
Zero error (Z)=···cm (to be added/subtracted)

No. of obs.	Main Scale reading in cm. (a)	Vernier Scale reading (v)	Value of Vernier Scale in cm. (v)× v.c. (b)	Total reading (a)+(b) cm.	Mean reading in cm.
1. 2. 3. etc.					

The corrected mean thickness/diameter/depth=···±···Z=···Cm

2-5. The travelling microscope. The *travelling microscope* is essentially a microscope (M, Fig. 2.7) capable of independent horizontal and vertical travel. The displacement in either direction can be read off with the help of a scale and *vernier*. The microscope axis may be fixed vertically, horizontally or at an angle to them by means of the screw X. S_1 gives the microscope a slow horizontal displacement, but it does not work unless the screw F fixes the microscope. S_2 is a similar screw for vertical motion. E is the eyepiece and O the objective. S is the stage on which the object is placed. The microscope is focussed on it by means of the screw C. The levelling screws attached to the base make the stage horizontal and the pillar vertical.

The focal length of the objective is ordinarily 1 or 2 inches. The horizontal and vertical ranges of travel are about 15-20 cm.

The instrument is sometimes referred to as the *vernier microscope*.

Before taking a reading, **always focus the eyepiece on the**

cross-wires. Then adjust the microscope tube (through C) until there is no parallax between the object and the cross-wires.

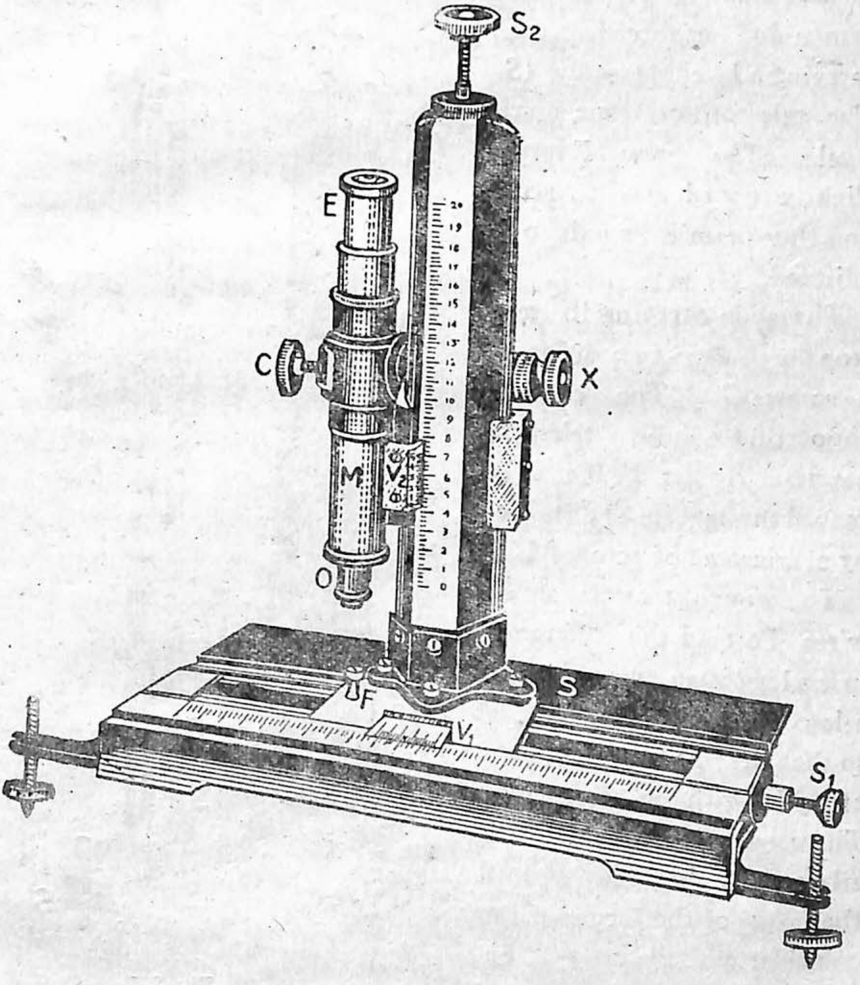


Fig. 2.7

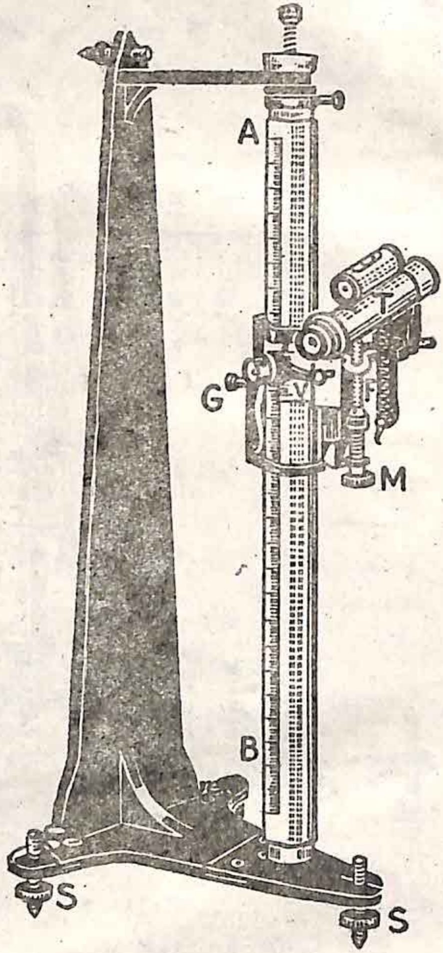
2·6. The cathetometer. When the vertical range of a travelling microscope is insufficient for a given purpose we use a cathetometer. The cathetometer (Fig. 2.8) is an instrument used for measuring vertical distances of about 50 cm or more. It consists of a graduated rod *AB* which can be adjusted to be vertical.

The rod carries a slide, to which is fixed a telescope T with its axis horizontal. T can be rotated along with AB about a vertical axis.

The stand on which the rod is mounted has three legs, each carrying a levelling screw (S). The telescope carries a spirit level. The screw F serves slightly to tilt the telescope and thus permits its axis to be adjusted.

The slide carrying the telescope may fixed in position by a screw G. The carriage supporting the telescope carries a vernier V. It may be moved through small distances by a micrometer screw M.

The telescope carries cross-wires. To read the difference in level between two points the telescope is focussed on the first so that the image of the point coincides with the cross-wires. The vernier is then read. The telescope is then moved until the image of the second point coincides with the cross-wires. The vernier reading is taken again. The difference between the readings gives the vertical distance between the points.



Fig, 2.8

In using the instrument care must be taken to ensure that

(1) The rod AB is truly vertical ;

(2) The axis of the telescope is horizontal ;

(3) The object is accurately focussed on the cross-wires.

The necessary adjustments are as follows :

(*a*) Turn the rod *AB* till the telescope is parallel to the line joining two of the levelling screws of the base. (Some cathetometers have two adjustable screws, the third leg being supported on a pin of fixed height. In such cases, the line to which the telescope is set parallel should pass through the fixed pin and any other screw). The bubble of the spirit level will generally be found to be away from the centre of its scale. Bring the bubble *halfway* back to the centre by turning the screw *F*.

For the other half turn the two base screws (those mentioned) by equal amounts *in opposite directions* at the same time until the bubble reaches the centre. (Note that these are the screws which form the imaginary line to which the telescope axis was set parallel. If, instead of two adjustable screws, you have a fixed pin and one screw, turn that screw only.)

(*b*) Next rotate the rod *AB* through 180°. If the bubble is not at the centre, bring it halfway back by the screw *F* and the other halfway by the previous two base screws.

(*c*) Now turn the rod until the telescope is at right angles to the previous line joining the two base screws. Bring the bubble back to the centre by turning the remaining levelling screw at the base.

In general it will be necessary to repeat the adjustments (*a*), (*b*) and (*c*) several times. The bubble will finally remain at the centre, whatever the direction in which the telescope is turned.

2·7. The optical lever. This simple piece of apparatus is ordinarily used for measuring *small angles*. It consists of a trianglar piece of metal (Fig. 2.9 ; left) provided with three short legs at the corners and has a small plane mirror attached at right angles to the metal plate, and parallel to the line joining the legs which are close together. In some cases the mirror may rotate about a horizontal axis.

Principle and method of use. The lever is used to measure a small change of angle and hence a small increase in length.

Consider a narrow beam of light incident on the mirror at a small angle and received after reflection on distant screen, distant

D from the mirror (Fig. 2.10). If now the mirror is tilted by a small angle α, the spot of light on the screen will be shifted by 2α. Hence if d is the linear shift of the spot, $2\alpha = d/D$.

Suppose the mirror was tilted by turning it through a small angle α about the axis joining the tips of the two supporting legs below it. Then the other leg must have been displaced by $p\alpha$, where p is the perpendicular distance between the tip of the third leg and this axis (Fig. 2.9). Knowing p, the displacement $p\alpha = x$ may be measured.

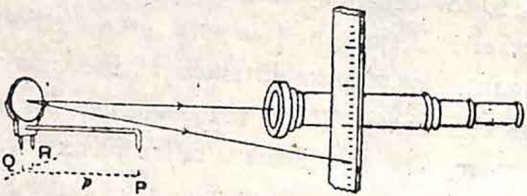


Fig. 2.9

To find p, take an imprint of the legs (points P, Q, R in Fig. 2.9) on a piece of stiff paper. Join the points forming the axis and drop a perpendicular from the third point on the axis. The perpendicular distance can now be measured with a pair of dividers and a diagonal scale.

Instead of a lamp and screen, we generally use a telescope and scale. The axis of the telescope is almost normal to the mirror. The image, formed by the mirror of a vertical scale correctly placed close to the telescope may then be seen in the telescope. As the mirror tilts, the mark of the scale coincident with the cross-wires changes in value (Fig. 2.10).

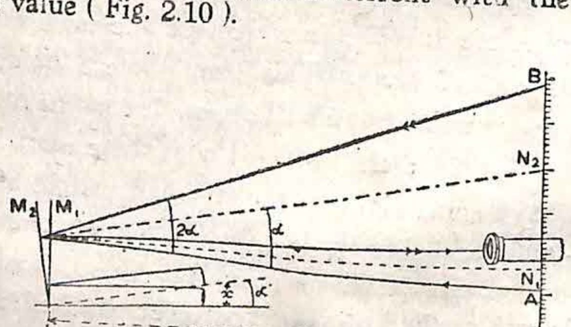
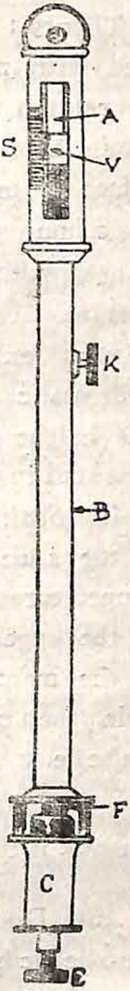


Fig. 2.10

[Light from A on the scale enters the telescope after reflection from the mirror at the position M_1. When the mirror is tilted into the position M_2, light from some other point B will enter the telescope. $AB = d$. The angle of tilt $a = d/2D$]

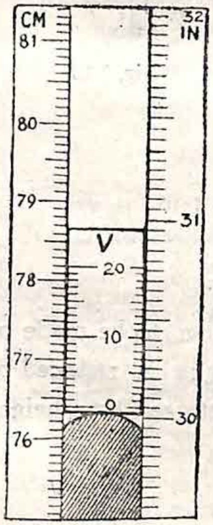
To set up the scale and telescope, adjust the mirror so that its plane is vertical. Place the telescope at the same vertical height as the mirror and point it almost normal to the mirror. Move about a lamp near the telescope until you see maximum light in it. Keep the lamp there and focus the telescope until a clear image of the lamp is seen. Then move both the lamp and the telescope closer together, keeping a clear image visible all the while. Do so until the lamp is close to the telescope and just behind the objective. Now place the scale behind the lamp. Its image will be seen in the telescope. If necessary, illuminate the scale.



Fig, 2.11

2·8. To read a Fortin's barometer and make corrections :

Apparatus : A Fortin barometer acts on the principle of Torricelli's experiments. In Fig. 2.11, *C* is a mercury cistern in communication with the atmosphere, over which a glass tube *A*, filled with mercury and closed at the top, is inverted. The two are enclosed in a metal tube B on which a scale *S* is etched. There is also a vernier *V* which can slide in a slot made in the metal tube. The tube is so slotted as to make the highest part of mercury column visible (shown separately in Fig. 2.12). The zero of the scale starts from the tip of an ivory pointer *F* which projects downwards from the ceiling of the cistern.



Fig, 2.12

The lower part of the instrument is shown magnified in Fig. 2.13. The surface of the mercury in the cistern can be adjusted by the screw E so that the tip of the ivory pointer F just touches it. The bottom of the cistern is made of leather.

Theory : If a tube, about a metre long, is completely filled with mercury and inverted over a trough of mercury, the column comes down a distance and remains steady at a certain height. The atmospheric pressure, pressing on the free surface of mercury in the wider vessel, supports the weight of the column of mercury. The height of the mercury column changes with the change of atmospheric pressure. The condition for balance is: Pressure exerted by the atmosphere= Hydrostatic pressure exerted by the liquid. The height of the mercury column can be measured in centimetres.

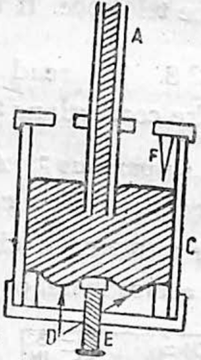


Fig. 2.13

(*i*) *Scale correction.* Let the graduations of the scale be correct at $t^\circ C$, and let the temperature of the barometer at the time of the experiment be t. If h is the height of the mercury column as found from the scale, then correcting for the expansion of the scale. we shall have the true height

$$H=h\{1+\alpha(t-t_0)\}$$

where α is the C.L.E. of the material of the scale.

(*ii*) *Density correction.* To enable comparisons to be made of barometric heights at different places, the height is reduced to that of a mercury column at 0°C. The relation between true height H at t°C and height H_0 at 0°C is given by

$$H_0=\frac{H}{1+\gamma t}$$

where γ is coefficient of real expansion of mercury.

Combining the above two equations we may write

$$H_0=\frac{H}{1+\gamma t}=\frac{h\{1+\alpha(t-t_0)\}}{1+\gamma t}=h\{1-\gamma t+\alpha(t-t_0)\}$$

where h is the height as read, and H_0 the corrected height.

Instructions. (*i*) Determine the vernier constant of the scale S in centimetres.

(*ii*) Adjust the mercury surface by the screw E so that the ivory pointer F just touches it. This happens when the image of the tip of the pointer in the mercury coincides with the tip of the pointer itself.

(*iii*) Keep your eye at the level of the convex top of mercury column. Slide the vernier by the screw K and so set it that its lower edge is tangential to the curved mercury surface (Fig. 2.12).

(*iv*) Take the reading of the main scale and also of the vernier. Repeat several times by resetting the mercury level and the vernier. Note the temperature at the time of experiment as well as the elevation and latitude of the place.

Record data as follows :

Experimental results :

Vernier constant :

Smallest scale div. =···mm

···vernier divisions =···scale divisions

vernier constant = 1 scale div. − 1 vern. div.

=···mm=···cm

Height of mercury column :

No. of obs.	*Main scale reading* (cm) (*a*)	*Vernier reading* (*v*)	*value of vernier reading* $v\times v.c.$ (cm) (*b*)	*Total* $(a)+(b)$ (cm)	*Mean* (cm)
1					
2					
3					

The atmospheric pressure=······cm of mercury at······°C at·········—(name of place) on···········(date) at·········hours (time)

Barometric height corrected for expansion of scale and reduced to 0°C=···cm.

2·9. The screw gauge. It is an instrument for measuring short lengths with a precision of about 0·01 mm. The screw gauge (Fig. 2.14) has a U-shaped piece of steel provided with two arms. A fixed stud C is attached to one arm as shown in the figure. To the other arm is attached a cylindrical tube (A). A linear scale (L) in centimetres is etched on it parallel to its axis. An accurately cut screw, provided with a collar (B), works in the tube and moves axially when it is rotated by the milled head (H). The bevelled end of the collar is divided into 50 or 100 equal divisions. When the end (D) of the screw touches the fixed stud, the zero of the circular scale (CS) should coincide with the zero point of the linear scale. If they do not, the instrument is said to have an *instrumental error*.

Principle. Conversion of the circular motion of the screw head into linear motion of the movable stud is the underlying principle of this instrument. Rotation of the screw head through equal angles displaces the screw axially through equal distances.

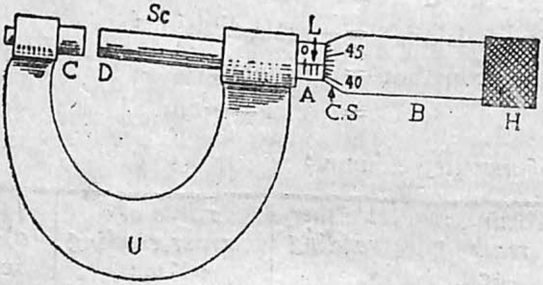


Fig. 2.14

The **pitch** of the screw is its axial displacement for a complete turn. The **least count** of the instrument is the axial displacement of the screw for a rotation of one circular division.

If the pitch of the screw is p mm and there are n circular divisions on the collar, then

$$\text{Least count} = \frac{\text{pitch}}{n} = \frac{p}{n} \text{ mm.}$$

To determine the *pitch*, give the screw head a number of complete turns. From the change in the linear scale reading you can find the pitch. Note the total number of divisions on the circular scale. Divide the pitch by the number of circular divisions. This gives the *least count* of the instrument.

To find the *zero error* of the instrument, turn the screw head till its end just touches the fixed stud. *Don't apply pressure.* If in this position the zero mark on the circular scale coincides with the reference line across the fixed scale, there is no zero error. If the zero of the circular scale *crosses* the reference line, *add* the zero error to the apparent reading. If it *fails to reach* the line, *subtract* the error from the apparent reading.

To measure the diameter of a wire with a screw gauge.

Find the pitch, least count and zero error. Hold the wire lightly between the fixed and movable studs. Don't press hard.

Take the fixed scale reading and note the division of the circular scale which coincides with the reference line. Take readings *at right angles*. Repeat readings at several places of the wire. Record as follows:

Constants of the screw gauge.

··· full turns = ···mm
Pitch (p) = ···mm
Total circular div.s = ··· (n)
Least count (p/n) = ···mm = ···cm
Zero error = ··· cm (to be added/subtracted)

Diameter readings. [(a) and (*b*) are at right angles.]

No. of obs.	Linear Scale reading in cm. (a)	Circular Scale reading (c)	Value of the Circular Scale reading (c) × l. c. (b)	Total reading in cm (a)+(b)	Mean reading in cm.
1. (a)					
(b)					
2. (a)					
(b)					
⋮					
etc.					

Corrected mean diameter = (mean reading) ± (*zero error*)
= ··· cm.

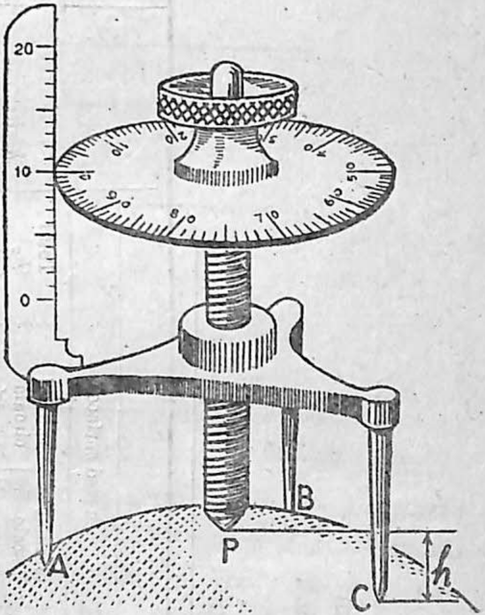
2-10. The spherometer. The spherometer is an instrument specially designed for measuring the radius of curvature of a spherical surface. It consists of a micrometer screw moving through a nut supported on three legs (Fig. 2.15). The points of the legs (A, B, C) form an equilateral triangle. The point P of the screw itself passes through the centre of this equilateral triangle. The circumference of the screw head is divided into 100 (or 50) equal divisions. The pitch of the screw is 1 mm (or 0·5 mm), so that each division ordinarily corresponds to 0·01 mm. A linear scale tells the number of complete revolutions which the head makes.

2-10.1. Experiment : Measurement of radius of curvature.

Determine the pitch and least count as in the case of a screw gauge.

To set the instrument place it on a sheet of plane glass and turn the screw till its tip just touches the plane. This can be determined by looking tangentially along the glass surface and finding when the gap between the tip of the screw and its image in the glass just vanishes. If the screw is pushed beyond this position the instrument rocks. Note the reading of the linear scale just below the screw head, and the reading of the circular scale just against the linear scale.

Now place the instrument on the spherical surface whose radius of curvature is to be measured, and adjust till all the four points (the three legs and the screw) touch the surface. Read the linear and circular scales as before. Let the difference between this reading and that on the plane glass be *h*. Repeat your observations several times and take mean *h*.



Fig, 2,15

Raise the screw point above the plane formed by the three points of the leg, place the instrument on a piece of stiff paper and press it lightly so that an imprint of the three legs is made on the paper. Measure each side of the triangle formed by the three points and take the mean. This should be done with a pair of dividers and a diagonal scale. Let it be *D*. Then the radius of curvature *r* of the spherical surface is given by

$$r=\frac{D^2}{6h}+\frac{h}{2}$$

Record as follows :

Exprimental results :

Constants of the spherometer.

··· full turns = ··· mm
Pitch (p) = ··· mm
Total circular div.s = ··· (n)
Least count (p/n) = ··· mm

No. of obs.	Reading on								$h=h_1-h_2$ cm	Mean h in cm
	glass plate				curved surface					
	Linear ccale cm	Circular scale	value of circular scole cm	Total (h_1) cm	Linear scale cm.	circular scale	valueof circular scale cm.	Total (h_2) cm		
1.										
2.										
3.										

Readings for D.

D (in cm)	Mean
1. 2. 3.	···cm.

Result

$$r=\frac{D^2}{6h}+\frac{h}{2}=\cdots+\cdots=\cdots\text{cm.}$$

2-10.2. Back-lash error. When a screw fits into a nut there is always some misfit between the two. The misfit is a minimum when the instrument is new and gradually increases with use. Due to this wear of nut and the screw, a reversal of the motion of the screw does not take place until it has turned through an angle depending on the extent of the wear. There is thus a lag between the linear and the circular motions when the direction of motion is reversed. This lag is known as *back-lash* error.

In using a spherometer or any device having a micrometer screw, *back-lash error must be avoided.* This can be done by *turning the screw backward by an amount greater than the back-lash error, and then slowly advancing the screw to touch the object.*

2-10.3 How to use a worn out spherometer : In the case of an old instrument, the screw becomes loose in the nut by use. Due to *this play between the nut and the screw, the edge of the circular* disc may indicate different readings on the linear scale for different tilts of the screw axis. This gives rise to some degree of uncertainty in the linear scale reading. In order to get rid of this difficulty an alternative method of taking readings, as stated below, may be followed.

Place the spherometer, first on the upper surface, and take the circular scale reading only when all the four legs touch the surface.

Place the instrument, without disturbing it, on the lower surface.

Turn the screw head until the four legs are again in contact with the surface. Take necessary precautions as in the previous method to ensure correct setting of the instrument on both the upper and the lower surfaces avoiding back-lash error.

Count the number of the complete turns of the screw head and observe the final circular scale reading.

While rotating the screw from the first position to the second, notice whether the circular scale reading is diminishing or increasing. Note this over the initial readings in your table. An arrow to the right may indicate an increase (say), and an arrow to the left a decrease.

From the initial and final readings of the circular scale and the number of complete turns, calculate the height h.

Repeat your observations several times and find mean h. Record your data as follows :

Experimental results :

Constants of the spherometer.

… full turns = … mm
Pitch (p) = … mm
Total circular div. s = … (n)
Least count (p/n) = … mm

No. of obs.	Initial circular Scale reading when the ↓screw just touches the upper surface (I)	No. of complete rotations (R)	Final circular scale reading when the screw just touhes the lower surface (F)	Additional no. of circular Scale divisions rotated (A).*	Total No. of circular Scale divisions rotated (T) =Rn+A	Value of these c. s. d. in mm. (h)=T×(l. c)	Mean h in mm
1.							
2.							
3.							
⋮							
etc.							

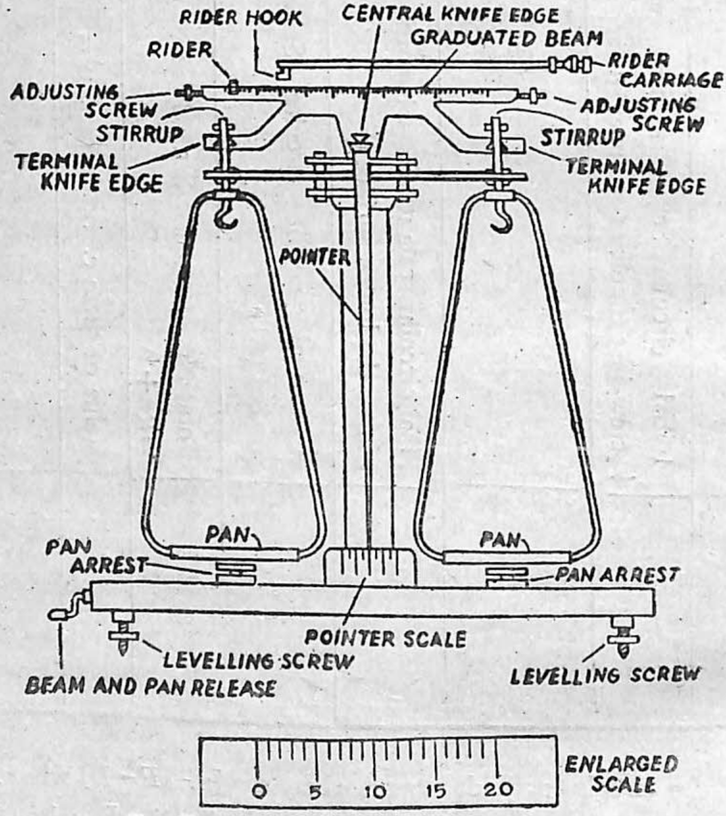
*(a) If the circular scale decreases, then $A=[n-(F-I)]$ when $F>I$ and $A=(I-F)$ when $F<I$

(b) If the circular scale increases, then $A=(I-F)$ when $F>I$ and $A=[n-(F-I)]$ when $F\leqslant I$.

Result

$$r=\frac{D^2}{6h}+\frac{h}{2}=\cdots$$

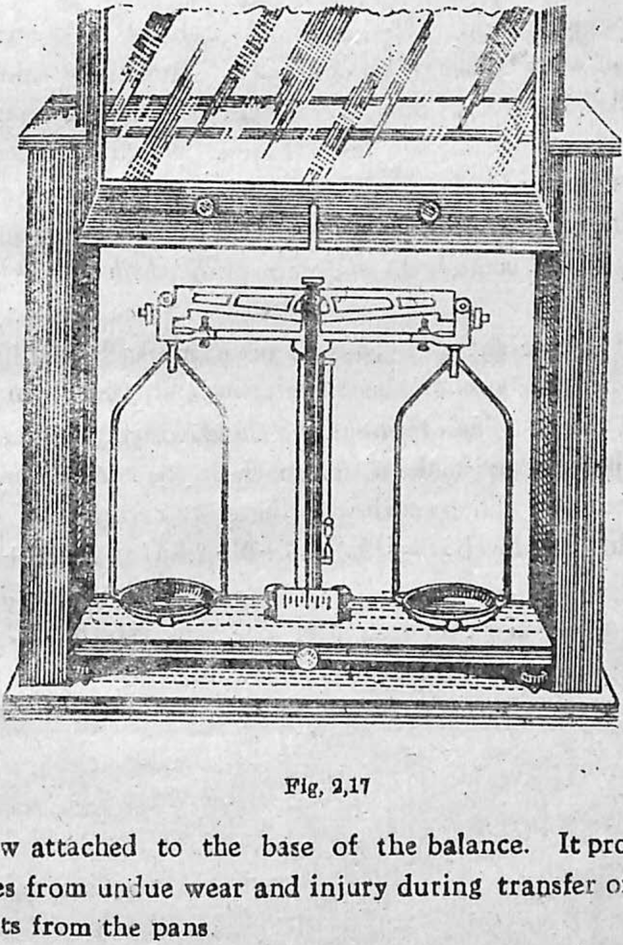
2-11. The common balance. The essential features of a physical balance are shown diagrammatically in Fig. 2.16. The beam is light and rigid. It is mounted at its centre on an agate knife-edge, which rests upon an agate plate attached to the pillar when the balance is in use. Each pan is hung from a suspension, called stirrup. An agate plane is attached to each stirrup. When in use the agate planes are lowered on to and supported by agate knife-edges fixed on the beam at equal distances from the central knife-edge.



Fig, 2.16

A long pointer attached to the centre of the beam moves over a scale at the foot of the pillar. The balance may be levelled with the help of levelling screws and a plumb line suspended from the pillar. Fig. 2.17 shows a balance in a case with the lid raised.

The balance is provided with a device whereby the agate knife-edges and planes may be slightly separated when the balance is not in use. This device is operated by means of a lever or a large screw attached to the base of the balance. It protects the knife-edges from undue wear and injury during transfer of weights and objects from the pans.



Fig, 2,17

Rider and its use : In some balances the beam is graduated from the centre outwards. In such cases adjustment of weights smaller than 10 mg can be readily made by moving a small piece of wire (called thr *rider*) along the beam by means of the *rider hook* and the *rider carriage.* Each division on the beam corresponds to 0·1 mg or 0·2 mg according to construction and to the mass of the rider, which is generally 10 mg. When the beam is graduated from one end a 5 mg rider is necessary. The rider should be at the zero mark when the zero position of the balance is being noted. While using a rider one must make sure, if necessary, by weighing, that it is of the right mass.

The weight box. The mass of a body is determined by comparison with bodies of known mass. These are contained in a box, called the weight box. It generally contains masses from 100 g to 10 milligrams or less. Masses weighing 1 g or more are ordinarily made of brass, while the lighter masses are of aluminium. The mass of each is imprinted on it. *These standard weights should be handled with a pair of forceps with which the weight box is provided.*

When the weight of a body has been balanced, record the value of each of the weights on the right pan and add them up before removing them. Then transfer the standard weights to the weight box, one by one, and make a tick mark on the corresponding value on your record. The record may therefore run thus :

Weight of the body $=(50+10+5+2+1)$ g $+(500+200+100+20+5)$ mg (with a tick mark on each after checking) $=68{\cdot}825$ g.

When there are several weighings to be recorded, the record will take space. But it is better to make sure than risk a mistake.

CHAPTER 3

PROPERTIES OF MATTER

Determination of Young's modulus by stretching.

Determination of Young's modulus *E by stretching* involves the measurement of the elongation *e* of a wire under the action of a stretching load. *e* is a small quantity and can be measured in different ways. This has given rise to the so-called different methods of measuring *E*. Thus we have

(A) *the Vernier Method*, in which *e* is measured with the help of a vernier scale,

(B) *the Micrometer Method* (also known as *Searle's method*), in which a micrometer screw is used for finding *e*, and

(C) *the Optical Lever Method*, in which an optical lever is used for finding *e*.

Apart from the measurement of *e*, there is no difference of procedure in the methods. We shall consider Searle's method only.

3·1. To determine Young's modulus by Searle's method. Description of Searle's apparatus. The wire to be tested (A, Fig 3.1) is suspended with another one (B) of the *same length and material* from the same suspension clip (generally attached to the ceiling). B is called the *comparison wire*. Its purpose is to compensate for any change in length of A due to temperature change.

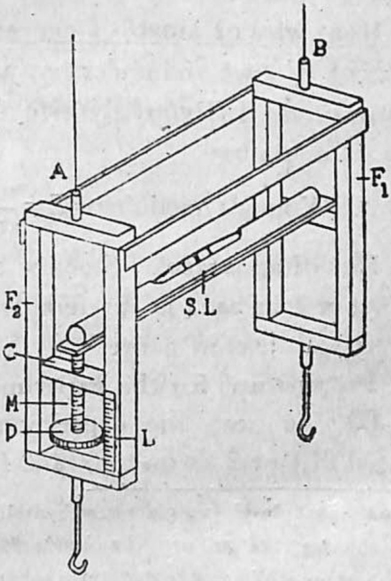


Fig. 3.1 (Searle's apparatus)

The comparison wire B terminates in frame F_1 which supports a dead load to keep B taut. The experimental wire A is attached to a similar frame F_2. The two frames are connected by cross pieces so that they are unable to move laterally relative to each other. But F_2 may be depressed without affecting B when loads are hung from its lower end.

A spirit level* S.L. is supported at one end on a rigid cross bar of F_1. Its other end rests on the point of a micrometer screw M. M can move vertically through a rigid cross bar. The disk D attached to the other end of M is divided into 50 or 100 circular divisions. As D is turned, M moves up or down. The extent of vertical motion of M is read off from the linear scale L and the circular scale on D. (Compare the action of a screw gauge or spherometer screw.)

The wire A will also have a dead load keeping it free of kinks. The spirit level is adjusted to be horizontal by turning D. This gives the initial reading.

Theory. When a force is applied to stretch a wire, it increases in length. The ratio of the *tensile stress to the tensile strain* is called Young's modulus.

If a wire of length l cm and radius r cm is stretched by a force of W g-wt and undergoes an elongation of l' cm, then the tensile stress is $Wg/\pi r^2$ dynes/cm^2. The tensile strain is l'/l, which is a pure number.

$$\therefore \text{ Young's modulus} = E = \frac{\text{stress}}{\text{strain}} = \frac{Wg/\pi r^2}{l'/l} \quad \frac{\text{dynes}}{\text{cm}^2}$$

List of apparatus. Searle's apparatus ; a set of equal weights ($\frac{1}{2}$ kg or 1 kg each), preferably slotted ; a long straight stick ; metre scale ; screw gauge.

Instructions for the experiment.

(1) To keep the experimental wire (A) free of kinks, place a load of 1 or 2 kg on the stand for slotted weights attached to the

---

*A spirit level is a glass tube containing alcohol and a bubble of air. The tube has the form of an arc of a circle. It is mounted in a metal tube with a plane flat bottom. When the bottom is horizontal, the air bubble is at the top centre of the glass tube, which it convex upward. A line on the glass tube marks this central position. If the centre of the bubble is on this line flat bottom is horizontal.

wire. Treat it as a 'dead load' and don't take it into consideration in your calculation of stretching loads. (Note it as 'dead load.')

(2) Measure the length l cm of the experimental wire from its point of suspension to the point of attachment to the frame F_2. Do it with the long stick and the metre scale.

(3) Take six sets of readings of the diameter d of the wire at three places (taking two readings in perpendicular directions at each place). Calculate the cross-sections of the wire from the mean value of d.

$$(S=\tfrac{1}{4}\pi d^2 = 0{\cdot}785d^2)$$

(4) Ascertain from your teacher-in-charge the breaking stress. Calculate the breaking load (breaking stress × area of cross-section) of the wire (that is, the minimum load at which the wire will snap). Don't apply a load more than half this value, (called limiting load) for you may then exceed the elastic limit. If this limit is exceeded, stress and strain will no longer be proportional to each other.

Breaking stresses (kgf/mm²)

Brass	35-55	Steel (ordinary)	112
Copper (annealed)	28-31	,, (tempered)	155
Iron (hard drawn)	54-62	,, (pianoforte)	186-233

(5) Ascertain the constants of the micrometer. Adjust the spirit level with the micrometer screw till the bubble is at the centre. Note the circular scale reading of the micrometer with only the 'dead load' on the pan, and take this reading as the reading for zero load.

(6) Increase the stretching load by ½ or 1 kg at a time and note the corresponding circular scale reading of the micrometer and number of complete rotation of the circular disc, if there is any, after making the spirit level horizontal. Take at least five such readings. *Use the five or so topmost admissible values of the load.*

(7) Reduce the stretching loads by the same amount as while increasing, and read the micrometer each time. Do so until you reach the dead load. (Don't remove the dead load. All readings are to be taken after the spirit level has been made horizontal).

(8) Take the mean value of the two readings you got for a particular stretching load W while the loads were increasing and while they were decreasing. The difference between this reading and that with only the dead load, is the elongation l' for load W. Thus you get five pairs of values of W, l'.

(9) Plot the W, l' points with W (load) along the x-axis and l' (elongation or extension) along the y-axis. They should lie on a straight line passing through the origin ($W=0, l'=0$). If they do not appear to do so, calculate the mean value of $\overline{W}$ of the stretching loads W you have used. Don't include the dead load. Find also the mean value $\overline{l'}$ of l', the elongations you have measured.

Plot the point $\overline{W}, \overline{l'}$ you so find, and join it to the origin.

This straight line is the best straight line* for the given data.

(10) Draw the straight line graph and choose on it a remote point P which passes through the corner of a small square. Determine the values of W and l' for this point, and use them in your formula for E. Take $g=980$ cm/s^2. Since the value of d may not contain more than two significant digits, your final result will have uncertainty in the second significant digit.

Experimental results :

Dead load = ··· kg.

Length l of wire (cm)	(i) ··· ; (ii) ··· ; (iii) ··· Mean l = ···cm.

Constants of the screw gauge **:**

···full turns = ···mm

Pitch (p) = ···mm

---

*The result follow, from the *method of least squares* in *statistical theory* on some simplifying assumptions.

Total circ. div.s (n)=···

Least count (p/n)=···mm

Zero error=···mm (to be added/subtracted)

Diameter and cross-sections of the wire :

[(a) and (b) are at right angles]

No. of *obs*	Linear Scale reading mm (l)	Circular Scale reading (c)	Value of Circular scale reading (c)×l.c.=(v) mm	Total d'=(l)+(v) mm	Mean diameter d' mm	Corrected diameter d=d'±z mm
1. (a)						
(b)						
2. (a)						
(b)						
etc.						

Mean corrected diameter (d)=···mm=···cm.

Cross-section $s=\pi d^2/4=\cdots$ cm^2

Limiting load **:**

Breaking stress=···kgf/cm^2 (supplied).

∴ Breaking load=cross section × breaking stress=···kgf.

and limiting load=$\frac{1}{2}$ × breaking load=······kgf.

Constants of the micrometer **:**

···full turns=···mm

Pitch (p =···mm

Total circ. divs (n)=···mm

Least count (p/n)=···mm=···cm.

Lead-extension date :

(The loads are in excess of the dead load)

[(i) for load increasing and (ii) for decreasing]

No. of obs.	Load W kg)	Initial cir. sc. reading (I)	No. of complete rotation (R)	Final cir sc. reading (F)	Additional no of cir. sc. div. rotated (A*)	Total no. of cir. sc. div. rotated $=Rn+A$	Mean of the two elongation (M)	Mean elongation in cm. = $M \times l.c$	Total elongation in cm (l)
1. (i)								...(a)	$a-a$
(ii)									
2. (i)								...(b)	$b-a$
(ii)									
3. (i)								...(c)	$c-a$
(ii)									
etc.									

[*If the circular scale decreases, then $A=[n-(F-I)]$ when $F>I$

and $A=(I-F)$ when $F<I$

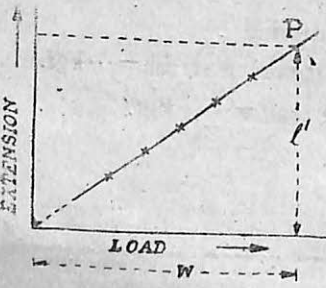
If the circular scale increases, then $A=(I-F)$ when $F>I$

and $A=[n-(F-I)]$ when $F<I$]

Mean load $\overline{W}$ (mean of column 2) = ···kg = ···g.

Mean extension $\overline{l'}$ (mean of last column) = ···mm = ...cm.

Result. The W-l graph is drawn (Fig. 3.2). From the point P on the graph, I find that for $W = \cdots$kgf, $l' = \cdots$ mm $= \cdots$ cm. Taking $g=980$ cm/s^2 and putting these values in the equation for E, I get



Fig, 8.2 (Wl' graph)

$$E = \frac{\cdots \text{kgf } (W)}{\cdots \text{cm}^2\ (S)} \cdot \frac{\cdots \text{cm } (l)}{\cdots \text{cm } (l')}$$

$$= \frac{W \times 100 \times 980 \text{ dyn}}{S \text{ cm}^2} \cdot \frac{l \text{ cm}}{l' \text{cm}}$$

$$= \cdots \text{dyn/cm}^2$$

Alternative method of calculation. Insted of drawing the graph, the values of $\overline{W}$ and $\overline{l'}$ may be substituted in the formula for E. [According to the 'method of least squares' in statistical theory, the best graph passes through the origin and the mean point (W, l'). The authors are in favour of this method. Drawing the (W-l') graph shows how the individual points lie off the best straight line.]

[The item below, that is, 'Method followed,' is a specimen meant to show the student how to write it.]

Method followed

(1) A dead load of 2 kg each was placed on the pans attached to the experimental and comparison wires to keep them taut. This load was not included in calculating the stretching load.

(2) The length and cross-section of the wire were determined.

(3) The breaking load was ascertained. I did not apply more than half this load as it might exceed the elastic limit.

(4) The least count of the micrometer was determined. The circular scale reading with only the dead load was noted. It is the reading for $W=0$.

(5) The load on the pan was increased by 1 kg at a time. I went up to···kgf. The corresponding circular scale reading and number of full rotation were taken each time.

(6) The loads were then diminished by the same amount at a time, and the corresponding reading taken, till I reached the dead load

(7) The elongation (l') for a load W was calculated from the mean reading for that load and the initial reading.

(8) The W-l' graph was drawn. It was a straight line through the origin. A point P on the corner of a square through which the graph passed was chosen and the values of W and l' corresponding to it were used for calculating E

Precautions. (1) The experimental wire should be free from kinks. A dead load must be placed on the pan to keep the wire taut.

(2) The total load (including the dead load) must not be greater than half the breaking load of the wire. A greater load may cause it to exceed the elastic limit.

(3) The screw must be rotated in one direction to avoid backlash erorr when a particular set of readings are noted.

3-1.1. Estimating the error in the result.

E depends on the measured quanities W, d, l, l' in the manner

$$E=k\,W\,d^{-2}\,l\,l'^{-1}$$

(d is the diameter of the wire, k is a constant, here equal to $4/\pi$.)

From formula 1-13.1,

$$\frac{dE}{E}=\frac{\delta W}{W}+2\frac{\delta d}{d}+\frac{\delta l}{l}+\frac{\delta l'}{l'}$$

Each term on the right-hand side of this equation gives the contribution of the relative error of the respective quantity to the relative error of the result. Let us consider each such term in turn.

δW is the absolute error in W. It is not a measuremental error. We accept the values of W as stated, but we do not know how far correct they are. δW is really a 'guarantee error' (Sec. 1-4.1), but is not known. So we take $\delta W=0$ (though a commercial 1 kg weight may differ from the true value by 5g or even more depending on the manufacturer). (In practice, $\delta W/W$ may be $5/1000=0{\cdot}005$ or 0·5%. It may be even higher.)

δd is the absolute error in d. d is generally of the order of 1 mm. The screw gauge measures up to 0·01 mm. A reasonable estimate of δd will be 0·01 mm (See table ; Sec. 1-8). So $\delta d/d$ is of the order of 1%. The contribution of this error in d to the relative error in E is *twice* this (that is, 20%), because E depends on the square of d

l is generally greater than 2 metres. So, even if we make an error of 1 cm in measuring l, its contribution to the relative error of the result will be less than 1/200 or 0·5%. The actual error is less than this, being determined by the position of the points of fixation of the wire at the two ends. *Taking three readings has been recommended to eliminate any gross error.*

The elongation l' is the smallest quantity we measure. So *$\delta l'/l'$ has the highest value of all the relative errors.* Taking $\delta l' = 0{\cdot}01$ mm (arbitrarily ; Sec. 1-8), find $\delta l'/l'$ from your data. You may be shocked to see how large it is.

We have ignored $\delta W/W$, found $\delta l/l$ to be 0·5% or less, $\delta d/d$ to be about 2%, and $\delta l'/l'$ much greater. *Our effort should therefore be to reduce $\delta l'/l'$ to around 2% or so. This will make the percentage error in the result to be about 5%.* The precision in the result will then be 1 in 20 (5%). If so, we may state the result as $E = \cdots \pm$ 5%. But remember $\delta l'/l'$ in the work done is well above 2%. So the final percentage error is greater.

Since $\delta l'/l'$ far exceeds other relative errors, using formula 1-14.1 will give little consolation.

3-1.2. Oral questions.

1. What is Young's modulus ? On what does it depend ? What are its units in the cgs system ?

2. What is elastic limit ?

3. Explain the terms 'longitudinal stress' and 'longitudinal strain'. What are their units ?

4. Why is it necessary to have another wire of the same material as the experimental one ? Should they have the same diameter ?

5. What is 'dead load' ? Why is it used ?

6. Why do you take readings twice, once while the load is increasing and again when it is decreasing ?

7. Explain how you drew the graph and used it.

Answers.

1. It is the ratio of a longitudinal stress to the longitudinal strain it produces, so long as the elastic limit is not exceeded. E depends on the material and to some extent on the temperature. It is independent of the diameter or length of the wire. In dynes/cm^2 units.

2. If a body is deformed by applying a force, ordinarily the body regains its original size and shape when the deforming force is removed. But if the applied force exceeds a limit, the body may be left with a permanent change of shape or size. This limit is called the 'elastic limit'.

3. A stress is a force per unit area. A longitudinal stress is one applied parallel to a length. It may be a tensile stress or a compressive stress. Longitudinal strain is the change in length per unit length. Stress is expressed in dynes/cm^2 units. Strain is a pure number and does not require any unit.

4. If the room temperature changes, the length of the experimental wire will also change. The second wire is used for correcting for this change. The change in length is the same in both wires due to the temperature. So the micrometer readings are not affected. The wires need not have the same diameter, as temperature affects them equally.

5. The 'dead load' keeps the experimental and comparision wires free of kinks. If there is a kink (a little bending), straightening of wire will lower its end without any change of actual length. Presence of a kink will thus vitiate results.

6. To reduce errors of adjustment

7. See items (8) and (9) under 'Instructions for the experiment'. The (0, 0) point should be on the graph.

Test yourself.

[*We shall not provide answers to the questions under this head. The questions are intended to induce some thinking and generate self-confidence in the student. He has all the material (in this book or his text book on **Properties of Matter**) to find the answers.*]

1. What do you understand by Hooke's law ? Breaking stress ? Why have you limited yourself to a maximum load ? What undesirable effects may take place if you go on increasing the load ?

2. Why do you measure the diameter in perpendicular directions at a given place, and also at different places ?

3. Can Young's modulus be determined by compressing a rod and measuring the contraction ? State how your answer is consistent with the defination of Young's modulus.

4. Is elongation of the experimental wire accompanid by any contraction of its diameter ? Do you think that the contraction, if any, will be measurable by the instruments you are using ?

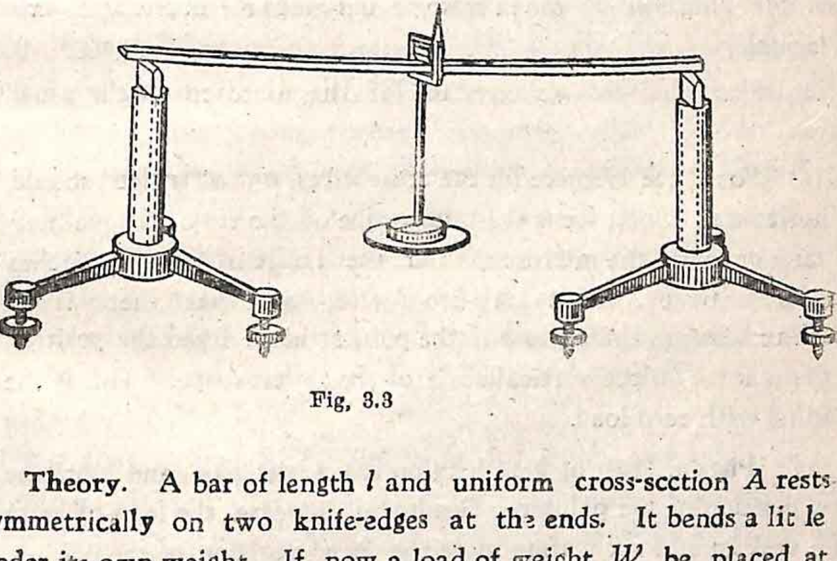
5. Will it make any difference in the value of the ratio longitudinal stress to longitudinal strain (i) if the wire is free to contract, (ii) if any lateral change of dimension is prevented ?

6. In this experiment you have measured a length, a diameter and an elongation. Which of these quantities should be measured with particular care and why ? [Find answer from Sec. 3-1.2.]

7. What is the correct number of significant figures in the result you have stated ? [See Secs. 1-9, 1-10 and 1-11]

3-2. To determine Young's modulus of a beam by flexure

[**Description of apparatus.** The experimental material is taken in the form of a rectangular bar about a metre long and of uniform cross-section. It rests horizontally and symmetrically on two parallel steel knife-edges (Fig. 3.3). The knife-edges are fixed on two heavy iron stands provided with levelling screws. The bar carries at its mid-point a vertical pointer and also a hanger, on which weights can be placed for depressing the bar. A microscope sliding along a vertical scale (Sec. 2-5) is suitably placed to see the tip of the pointer.]



Fig, 3.3

Theory. A bar of length l and uniform cross-section A rests symmetrically on two knife-edges at the ends. It bends a little under its own weight. If now a load of weight W be placed at its mid-point, it will produce a depression δ below the original value. Then E, the Young's modulus of elasticity of the material of the bar, is given by

$$E=\frac{Wl^3}{4bd^3\delta} \qquad (3\text{-}2\,1)$$

where b and d are the breadth and depth respectively of the bar.

Apparatus. Searle's apparatus for flexure of beam with necessary accessories, such as hanger with central pin, a set of slotted

$\frac{1}{2}$ kg or 1 kg weights, metre scale, spirit level, screw gauge, travelling microscope and reading lens.

Instructions for the experiment. (1) Draw a well defined transverse line through the mid-point of the bar. Also draw two other lines parallel to the ends and about 2 to 3 mm from the end.

Place the bar on the two knife-edges so that it rests on the two marked lines equidistant from the ends. Adjust the bar to be horizontal with the help of a spirit level placed in its middle. Attach the hanger and the pointer at the mid-point of the bar. Place a travelling microscope suitably to see the tip of the pointer. *Level the platform of the microscope and make the microscope axis horizontal.*

(2) Find the vernier constant of the microscope in the usual way.

(3) Focus the eyepiece on the cross-wires, one of which should be horizontal. Then focus the microscope on the tip of the pointer. So raise or lower the microscope that the image of the top touches the image of the horizontal cross-wire. See that there is *no parallax* between the wires and the pointer head. Read the position of the pointer on the vertical scale of the microscope. This is the reading with zero load.

(4) Place a load of $\frac{1}{2}$ or 1 kg on the scale pan and note the new position of the pointer. Gradually increase the load by steps of $\frac{1}{2}$ or 1 kg and each time note the new position of the pointer. Make 6 or 8 such observations. Now decrease the load stepwise and read the scale as before. Thus for a given load you will have two readings, one while the load is increasing and the other while it is decreasing. Take the mean of these two values as the reading for that load.

(5) Remove the bar taking care not to disturb the positions of the stands. Place a metre scale across the knife-edges with the scale-marks vertical. Measure the length (l) between the knife-

edges to the nearest millimetre Take at least *six* readings*, using different parts of the scale, and note the mean. Measure the brerdth b at three different places of the bar with the screw gauge.

(6) Measure the depth d of the bar with the screw gauge at *six* places along the entire length of the bar. As the expression for E involves the cube of the depth, a relative error of 1% in the value of the depth will contribute *three times* its value to the relative error in E. So special care should be taken to minimize the error in measuring the depth. (The depth being small, its relative error will be much greater than that of l. Hence the need for a much finer measuring instrument and use of the screw gauge.)

(7) Calculate the depression for each load. Plot the depression δ against the depressing load W. The experimental points should lie on a straight line passing through the origin (0,0). If they do not, calculate mean δ and mean W. Plot this point $(\overline{\delta, W})$ and join it to the origin (0,0). This is the best straight line** that can be obtained from your data.

(8) Choose a for point on the graph which passes through a corner of a small square. Find the depression and the load corresponding to this point and use these values of W and δ in Eq. 3-2.1 to calculate E

Noth that it is eqally valid to use mean δ $(\overline{\delta})$ and mean W $(\overline{W})$ in Eq. 3-2.1.

---

*Note that l occurs in the third power. Hence its contribution to the relative error of the final result is *three times* its own relative error (See Sec.s 1-13.1 and 1-13.2). l is ordinarily about 90 cm. Hence an error of 1 mm in its determination produces an error $3 \times (1/900)$ or 1 in 300, that is 0·3% in the final error.

**According to statistical theory, If there is a large number of points, each of low precision, and the relation is a straight line passing through the origin, join the origin to the point with co-ordinates $\bar{x}, \bar{y}$ (mean x and mean y) to get the best straight line stisfying the principle of least squares. This *simple method* gives results which have no more error than the earlier complicated methods of calculation (which were arbitrary).

[Record your results as follows.]

Experimental results :

Constants of the vernier microscope (vertical scale) :

Smallest scale division = ··· mm

··· vernier divisions = ··· scale divisions

Vernier constant = 1 scale div.—1 vern.div

= ··· mm = ··· cm.

Load-depression data :

Obs	Load (kg)	Readings (in cm) for						Mean reading (cm)	Mean depression δ (cm)
		Load increasing			Load decreasing				
		Main scale	Vernier	Total	Main scale	Vernier	Total		
1	0	...	...	...	...	...	...	...(a)	(a − a)
2	...	...	...	...	...	...	...	...(b	(b − a)
3	...	...	...	...	...	...	...	...(c)	(c − a)
4	...	...	...	...	...	...	...	...(d)	(d − a)
etc.									

Mean load $\overline{W}$ = ··· kgf = ··· gf ; Mean $\bar{\delta}$ = ··· cm

First graph : (Plot of last column against the second)

Second graph : [Straight line joining the point $(\overline{W}, \bar{\delta})$ to the origin (0,0). Compare the two graphs. Use the calculated values of $\overline{W}$, $\bar{\delta}$ in the equation for E.]

Length of the bar (l) between the two knife-edges :

(Scale placed at random)

Obs.	Right end (cm)	Left end (cm)	l (cm)	Mean l
1				
...				
6				... cm

Constants of the screw gauge :

··· full turns = ··· mm

Pitch (p) = ··· mm

Breadth (b) and Depth (d) of the bar (in cm) :

Total circular div.s $= \cdots (n)$

Least count $(p/n) = \cdots$ mm

Zero error $= \cdots$ mm(add/subtract)

Dimension	No. of obs.	Linear scale reading (in mm) (*L*)	Circular scale reading (*C*)	Value of the cir. sc. reading (in mm) $V = C \times l.c.$	Total $L+V$ in (mm)	Mean (in mm)	Corrected mean (in cm)
Breadth (*b*)	1. 2. 3. ⋮ etc.						
Depth (*d*)	1. 2. 3. ⋮ etc.						

Calculation : From the *second graph*, when load $(W) = \cdots$g,

depression $(\delta) = \cdots$cm.

Or,

Mean load $\overline{W} = \cdots$kgf$= \cdots$gf$= \cdots$g $\times$ 980 cm/s^2 = dynes.

Mean depression $\overline{\delta} = \cdots$cm.

Result : Substituting the above values and using other measured values

$$E = \frac{Wl^3}{4bd^3\delta} = \cdots \text{ dyn/cm}^2.$$

Method followed. (**A brief statement**)

1. I determined the constants of the vernier microscope, and screw gauge.

2. I marked the central line across the beam, and measured the breadth and depth of the beam.

3. The beam was supported horizontally on two parallel knife-edges near its ends, and the hanger and pin were fitted to it along the central line.

4. The platform of the microscope was levelled and the microscope axis made horizontal. It was then focussed on the pin head. The reading on the vertical scale was taken with no load on the hanger.

5. The load was increased gradually by steps of ··· kg, and the pin head reading taken each time. After ··· such readings the load was reduced by the same amount each time until there was no extra load on the hanger. During reduction of load, the pin head reading was taken every time. The mean of the two values for the same load was used for calculation.

6. After removing the bar, the distance between the knife-edges was carefully measured with the metre scale.

7. A load-depression graph was drawn from the data obtained. (This merely served to show how consistent the readings were.) The best graph is the one passing through the origin and the point defined by the mean value of W and δ. (This follows from the "method of least squares" in Statistics.)

8. In calculating the result, I therefore used the mean values of W and δ.

Precaution. As l and d occur in the third power in the expression for E these two quantities should be measured with as much precision as the instruments permit. Also, more readings of these quantities should be taken than for others.

3-2.1. Discussion of errors. From the working formula $E=Wl^3/4bd^3\delta$ (Eq. 3-2.1), it follows from Eq. 1-13.1 that

$$\frac{\partial E}{E}=\pm\left(\frac{\partial W}{W}+3\frac{\partial l}{l}+\frac{\partial b}{b}+3\frac{\partial d}{d}+\frac{\partial \delta}{\delta}\right)$$

The ∂'s are the absolute errors in the corresponding quantities. The fractions are the relative errors. (Here we take g as a fixed quantity, correct up to 3 significant figures.) This means that the relative error in the final result is the *sum* of the contributions of the relative error of each constituent quantity. If one of these quantities has a power p, then its contribution to the final (relative) error is p times its own relative error. This can be seen in the quantities l and d in the equation.

Let us consider the relative errors one by one. The data are taken from a student's record.

(*i*) $\partial W/W$. We do not exactly know by how much a stated weight W (say, 1 kg) differs from the standard weight. Generally, we take the standard weights as correct, that is, ∂W is taken as zero. Actually $\partial W/W$ may be as high as ±0·5%. (A so called 1 kg weight may be anything between 995 and 1005 g.) But this is ignored.

(*ii*) $\partial l/l$. $l = 80{\cdot}0$ cm. He took three values, all identical. The random error was scale-limited (Sec. 1-5.1). We may reasonably take ∂l as 0·5 mm = 0·05 cm. $\partial l/l$ is therefore $5/8000 \simeq$ 0·16% and *thrice* this value is about 0·5%.

(*iii*) $\partial b/b$. b varied between 0·651 and 0·656 cm for the 5 readings taken. For quick calculation, let us take ∂b as half the difference of the extremes. This is 0·003 cm. $\partial b/b$ is therefore 3/650 or ±0·5%.

(*iv*) $\partial d/d$. The bar used was a square one. ∂d was $\frac{1}{2}(0{\cdot}656 - 0{\cdot}656) = 0{\cdot}003$. $3 \times (\partial d/d)$ was therefore about ±1·5%.

(*v*) $\partial \delta/\delta$. For a 1 kg load, δ was 0·341 cm for load increasing and 0·348 cm for load decreasing. Hence we may take $\delta \simeq 0{\cdot}345$ cm and $\partial\delta = \frac{1}{2}(0{\cdot}348 - 0{\cdot}341) = \frac{1}{2} \times 0{\cdot}007 \simeq 0{\cdot}004$ cm. Thus $\partial\delta/\delta$ was about 4/345 or ±1·1%. The smallness of δ contributed about the same value to the final error as the depth d, though d occurs in the third power. Because of the largeness of l, $3\partial l/l$ was rather small.

$\therefore \quad \partial E/E = \pm(0{\cdot}5 + 0{\cdot}5 + 1{\cdot}5 + 1{\cdot}1) = \pm 3{\cdot}6\%$.

This is the maximum error. Treating the relative errors as independent and applying the formula 1-14.4, we find that error is probably nearer to 2%.

His calculated values of E varied between 20·10 and $20{\cdot}70 \times 10^{11}$ dyn/cm². This gives a mean value of $20{\cdot}40 \times 10^{11}$ dyn/cm². But the number of significant figures in the result should be three, and the result stated as $20{\cdot}4 \times 10^{11}$ dyn/cm^2.

So, the result in this case is

$E = 2{\cdot}04 \times 10^{12}$ dyn/cm^2 $\pm 2\%$.

Note that the values of E he obtained are within this limit.

3-2.2. Oral questions.

1. Define Young's modulus.

2. What do you understand by *stress* and *strain*. What are the units in which they are expressed ? In what unit is Young's modulus expressed ? Why is this the same as that of stress ?

3. What value of stress did you assume in calculating the final result ? What was the corresponding strain ?

4. What is Hooke's law ?

5. How do you assure yourself that in your experiment you have not exceeded the elastic limit ?

6. Would you exercise the same care in measuring the breadth and the depth ? Why ?

7. Does the weight of the beam affect the result ? How ?

Answers :

1. It is the ratio of a *longitudinal stress* to the *longitudinal strain* it produces, so long as the elastic limit is not exceeded.

2. See answers to questions 1 to 3 of Sec, 3-1.2.

3. The case is not one of applying a stress, noting the strain, and measuring their ratio. The experiment is one of noting the depression for a given load. Young's modulus enters indirectly.

4. Hooke's law states that within the *elastic limit*, a strain is proportional to the stress producing it.

5. The elastic limit was not tested in this case. If the load-depression curve is a straight line, we are within the elastic limit. When the same increase in load produces a greater depression, elastic limit is exceeded.

6. Breadth occurs in the first power and depth in the third power. Hence, in the final result, the contribution of the relative error in depth is three times its value. Breadth contributes its own relative error to the final result. Depth being smaller than breadth, the relative error in it is also larger. Hence depth must be measured with greater precision. (See Sec. 3-2.1).

7. Even if the weight of the beam is not negligible compared with the load, it does not affect our result, We have noted the increase in δ for increases in W. The position $\delta = 0$ takes care of the weight of the beam. That position is

below the horizontal level by an amount arising out of the weight of the beam. The same argument applies to the effect of projection of parts of the beam beyond the knife-edges.

Test yourself.

1. Young's modulus involves a longitudinal stress and a longitudinal strain. Where are such stresses and strains in this case ?

2. For a heavy beam you plot load along the x-axis and depression along the y-axis. Will the graph be (*i*) a straight line, (*ii*) a curved line curving upward, (*iii* a curved line curving downward, when you ignore the weight of the beam ?

3·3. To determine the modulus of rigidity by the statical method

Description of apparatus. There are various forms of apparatus that are used for the determination of the modulus of rigidity ; but the principle involved is the same. Two common forms generally found in the laboratories are described below.

The type of apparatus shown in Fig. 3.4 consists of a rigid iron frame provided with a heavy iron base standing on three levelling screws. The experimental wire is clamped at the centre of the upper frame-work by means of a screw S and carries a heavy cylinder K, called the *fly-wheel*, at its lower end to which it is clamped by another screw S′. Two threads, with one end of each attached to the cylinder and wound in the same direction, pass round it tangentially in opposite directions and carry two scale pans at their other ends after passing over two pulleys mounted on ball-bearings.

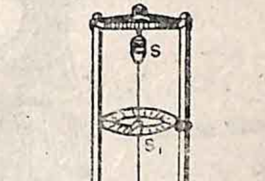


Fig. 3.4

A long pointer is attached to the wire near its lower end and moves over a horizontal circular scale (S_2) graduated in degrees. The wire should pass through the centre of this scale. There may be another pointer which can be attached to some other point on the wire and can move over a similar horizontal scale (S_1).

Second form. The other form of apparatus is shown in Fig. 3.5. Here the material, the rigidity of which is to be determined, is in the form of a rod (AB) of circular cross-section. It is mounted horizontally on a rigid frame with one end rigidly fixed. The other end is supported on a ball-bearing and carries a fly wheel F at the end. A piece of steel ribbon band, R, one end of which is attached to the fly wheel, passes round it and carries a scale pan at the other end. Weights are placed on the scale pan to produce the twisting couple. The rotation of the fly wheel is measured by the vernier.

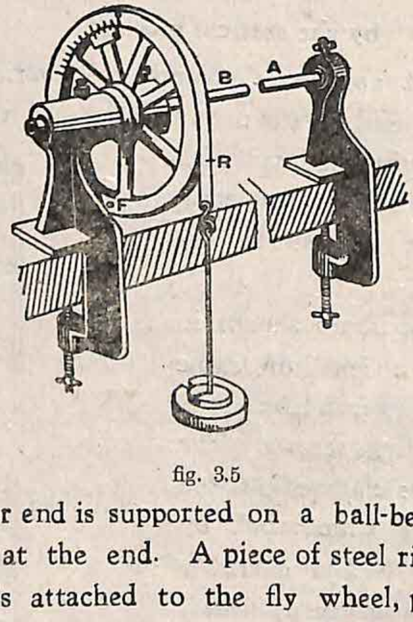


fig. 3.5

Theory. If a homogeneous wire of uniform radius r and length l be fixed at one end twisted at right angles to its length by a couple of moment C applied at the other end, the twist θ at the free end is given by the equation

$$C=\frac{\pi G r^4 \theta}{2l}$$

where G=the modulus of rigidity of the material of the given wire.

$$\therefore \quad G=\frac{2l}{\pi r^4}\cdot\frac{C}{\theta}$$

In this equation, if l, r and C are in cgs units and θ in radians, G will be in dynes per cm^2.

If the couple is due to a load of Mg acting with an arm R cm,

$C=MgR$ dyn-cm.

If the observed angle of twist is ϕ degrees,

$$\text{then } \theta=\frac{\pi}{180} \text{ radians.}$$

Substituting these values of C and θ, the equation for G reduces to

$$G=\frac{360\ lgR}{\pi^2 r^4}\cdot\left(\frac{M}{\phi}\right) \text{ dyn/cm}^2. \qquad (3\text{-}3.1)$$

In the case where there are two pointers, let l_1 and l_2 be the distances of the points of attachment of the pointers from the fixed end, and ϕ_1 and ϕ_2 be the corresponding twists produced at the points of attachment of the pointers. Then

$$G=\frac{360gRMl_1}{\pi^2 r^4 \phi_1}=\frac{360gRMl_2}{\pi^2 r^4 \phi_2}$$

$$=\frac{360gR(l_2-l_1)}{\pi^2 r^4}\cdot\frac{M}{\phi_2-\phi_1} \qquad (\ \text{-}3.2)$$

If all the quantities on the right-hand side are expressed in cgs units, the value of G is obtained in dyn/cm^2.

List of apparatus. Rigidity apparatus ; two sets of identical weights ; rod with two sliding pointers ; metre scale ; spirit level ; screw gauge ; slide callipers.

Instructions. (1) To level the instrument place a spirit level on the circular scale such that it is parallel to the line joining two of the levelling screws. Adjust any of the two screws to bring the bubble to the centre. Next place the spirit level at right angles to its former position and bring the bubble at the centre by adjusting the third levelling screw.

This ensures that the experimental wire passes through the centre of the circular scale. (But check it visually. The part of the circular disc where you placed the spirit level might have been curved).

If the pin at the lower end of K touches the frame, adjust the levelling screws to keep the pin free. This is very important. Otherwise there will be friction, which will reduce the effect of the applied couple.

(2) Measure the length of the experimental wire between the points of attachment of the clamp at the fixed end and the pointer at the remote end. For this purpose, use a rod with two sliding pointers on it, if available.

(3) Measure the diameter of the wire by means of a screw gauge at least at six different places along the entire length of the wire. At each place take two readings at right angles. As the expression for rigidity involves the fourth power of the radius, an error of 1% in the radius will cause an error of 4% in the final result. Hence much care should be taken in measuring the radius. Many more readings have to be taken for it than for any other quantity involved in the measurement. By this means the error in its measurement may be kept sufficiently low. The thinner the wire the larger the number of readings that should be taken. The screw gauge should be read to three significant figures, by eye-estimation if necessary.

(4) Determine the diameter of the fly wheel R, which is the arm of the applied couple, by means of a pair of slide callipers.

(5) Take readings of the pointer with no load on the scale pans, making sure that the fly wheel does not touch the frame.

(6) *Testing elastic limit.* If the wire is about a metre long, test by putting an initial load to produce a rotation of about one com-

plete turn. See if the pointer returns to the initial position after removal of the load. If it does, use $\frac{1}{6}$ to $\frac{1}{8}$ of this load at a time to produce rotation. If it does not, find the load that causes a rotation of about 360° without producing a permanent set. You are then within the elastic limit. Use about $\frac{1}{6}$ to $\frac{1}{8}$ of this load at a time.

(7) Place equal weights on the scale pans and take readings of the pointer. Increase the loads on both pans by equal steps and each time read the pointer. Take six to eight such readings.

(8) Repeat your observations for the same loads as you decrease them by equal steps.

(9) For a given load take ϕ as the mean of the two values that you get, one while the load is *increasing* and one while the load is decreasing.

Plot the twist ϕ against the load M.

The experimental points should lie on a straight line passing through the origin. If they do not, plot the mean value of ϕ against the mean value of M and join this point to the origin. You may use these mean values for calculation in Eq. 3-3.1.

Alternatively, from a point on the graph, as far away from the origin as is convenient, find the twist and the corresponding load. Substitute this value of M/ϕ in the formula for G.

Experimental results :

Length of wire in cm :

Obs.	1	2	3	Mean
Reading	···cm	···cm	···cm	···cm

Constants of the screw gauge :

···full turns =···mm
Pitch (p) =···mm

Total circular div.s $= \cdots (n)$
Least count $(p/n) = \cdots$mm
Zero error $= \cdots$mm (add/subtract)

Diameter of the wire in mm **:**

[(a) and (b) are at right angles]

No. of Obs.	Linear Sc. reading (mm) (L)	Cir. Sc. reading (C)	Value of circular Scale reading V= (C)×l.c. mm	Diameter L+V mm	Mean diameter d′ in mm	Corrected diameter $d = d' \pm Z$ mm	Radius $r = \frac{d}{2}$
1. (a)							
(b)							$\cdots$mm
2 (a)							
(b							
etc,							$= \cdots$cm

Constants of the slide callipers :

Smallest scale div. $= \cdots$mm
$\cdots$vern. div.s $= \cdots$scale div.s
Vernier constant $= \cdots$1 sc. div. $-$ 1 vern. div.
$= \cdots$mm $= \cdots$cm
Zero error $= \cdots$mm(add/subtract)

Diameter of the fly-wheel in cm **:**

[(a) and (b) are at right angles]

No. of Obs,	Main Sc. reading in cm (M)	Vernier reading (V	Value of Vernier reading in cm = V ×l.c. V)	Diameter = M + V in cm	Mean diameter D in cm	Corrected diameter $D = D \pm Z$ in cm.	Radius $R = \frac{D}{2}$ in cm
(b)							
2							
(b)							
etc.							

Load-twist data :

Obs.	Load (M) in g	Readings in degrees						Total twist in degrees		Mean twist in degrees
		Load increasing		Load decreasing		Mean				
		end I	end II	end I	end II	end I	End II	end I	end II	ϕ
1	0	…	…	…	…	…(a)	…(a)	…	…	0
2	…	…	…	…	…	…(b	…(b)	(b-a)	(b-a)	…
3	…	…	…	…	…	…(c)	…(c)	(c-a)	(c--a)	…
4	…	…	…	…	…	…(d)	…(d)	(d-a)	(d-a)	…
5	…	…	…	…	…	…(e)	…(e)	(e-a)	(e-a)	…
…	…	…	…	…	…	…(f)	…(f)	(f-a)	(f-a)	…

Calculation. Plot the last column against the second to see if you get a good straight line passing through the origin. If not, find mean M and mean ϕ. Plot this point and join it to the origin. This is the best straight line your data can give.

Result : From the graph, when load $(M)=\cdots$g, twist $\phi=\cdots°$ (degrees)

$$\therefore \quad G=\frac{360lgR}{\pi^2 r^4}(M/\phi)\ \text{dyn/cm}^2$$

$$=\cdots\cdots\cdots\text{dyn/cm}^2.$$

(g may be taken$=980$ cm/s^2 unless any other value is specified.)

Alternatively, use mean M and mean ϕ to calculate the result.

Method followed. (A brief statement)

1. I levelled the instrument so that the suspended system was free to turn without friction.

2. I measured the length and radius of the experimental wire.

3. The diameter of the flywheel was then measured, and the reading with zero load was taken.

4. To check that the elastic limit was not exceeded I placed enough load on the pans to produce a rotation of about 270°. I then removed the load and checked if the initial reading was restored. I found it so.

5 Then I increased the load from zero to nearly the above maximum value in six equal steps, and read the pointer each time. The loads were then decreased in equal steps as before, and the pointer reading for each step taken.

6. A $M-\phi$ graph was drawn to see how consistent the readings were. But in calculating the result I used the mean values of M and ϕ because this procedure was known to be the best according to the theory of errors in statistics.

Precautions. (*i*) While taking readings care was taken to see that the system was in equilibrium and there was no friction.

(*ii*) A test was made to see that the elastic limit was not exceeded.

3-3.1. Oral Questions.

1. Define modulus of rigidity.
2. What is a shear ? How is the shear applied in this case ?
3. How do you measure the strain in this case ?
4. How will the twist change (a) if the length of the wire alone is increased, (b) if its radius is increased ?

Answers.

1. When a body is *sheared* the ratio of the shearing stress to the shearing strain it producees is called the modulus of rigidity.

2. A shear is a tangential stress applied parallel to a plane of a body. Here, in twisting the wire we apply a couple perpendicular to the length of the wire. The plane of this couple is the plane of shear.

3. Here we measure the strain by the angle of rotation of the lower end (free end) of the wire.

4. (a) Eq. 3-3.1 shows that if l alone is increased, ϕ will increase proportionately. (b) If r alone is increased, ϕ will diminish as the inverse fourth power (that is, if r is doubled, ϕ will be 1/16 the earlier value).

3-4. To determine the modulus of rigidity by the dynamical method

Description of apparatus The simplest type of apparatus consists of a fairly large solid metal cylinder of uniform cross-section, suspended by means of the wire, the modulus of rigidity of which is to be determined. The wire is attached to a screw point at the top. The lower end of the wire is also attached to the cylinder by means of a screw so that the axis of suspension coincides with the axis of the cylinder. The whole instrument may be kept under a glass cover to protect it from draught.

Theory. When a sufficiently heavy body is suspended by means of a wire (weight of the wire being negligible compared to that of the body) and is allowed to make torsional oscillations about the axis of suspension, the time period T of the oscillations is given by

$$T=2\pi\sqrt{I/C} \tag{3-4.1}$$

where I is the moment of inertia of the body about the axis of suspension and C, the torsional couple exerted by the wire when twisted through an angle of one radian.

In the case of a wire of uniform circular cross-section and length l, C is given by the relation

$$C=\frac{\pi G r^4}{2l} \tag{3-4.2}$$

where r is the radius of cross-section of the wire and G its rigidity modulus.

$$\text{Therefore, } \frac{\pi G r^4}{2l}=\frac{4\pi^2}{T^2}I \text{ or } G=\frac{8\pi l I}{r^4 T^2} \tag{3-4.3}$$

Measuring l, I, r and T, G may be determined.

If the body used is a solid metal cylinder of mass M and radius R and is allowed to oscillate about its axis, its moment of inertia is given by the relation

$$I=\tfrac{1}{2}MR^2 \tag{3-4.4}$$

List of apparatus. Rigidity apparatus ; rod with sliding pointer ; metre scale ; screw gauge ; slide callipers ; stop-watch.

Instructions. (1) Detach the cylinder from its suspension and weigh it correct to 1 g by means of a rough balance. If the cylinder is not detachable, the value of its mass should be available from the teacher-in-charge. Measure the diameter of the cylinder with a pair of slide callipers and calculate the moment of inertia of the cylinder about its axis of symmetry.

(2) Suspend the cylinder (if detachable) by means of the experimental wire and measure the length of the wire between the point of suspension and the point at which the wire is attached to the cylinder. For this purpose, use a rod with two sliding pointers on it, if available .

(3) Measure the diameter of the wire by means of a screw gauge at six different places along the entire length of the wire taking two readings at right angles at each place. As the expression for rigidity involves the fourth power of the radius, many more readings have to be taken for it than for any other quantity involved in the measurement. The thinner the wire the larger the number of readings that should be taken. The screw gauge should be read to three significant figures, by eye-estimation, if possible.

(4) Mark a vertical line on the surface of the cylinder and set up a pointer facing the vertical line when the cylinder is at rest.

Twist the cylinder through an angle of about 60° and allow it to oscillate about the axis of supension. Damp out pendular oscillations if there by any. Check your stop-watch for zero error and make allowance for it, if there is any. (Better ask the teacher to adjust it.) Start the stop-watch when the vertical line crosses the tip of the pointer and measure the time for 50 oscillations if T is rather short, or 30 oscillations if T is rather long. The time for one complete oscillation is the interval between two succesive transits of the vertical mark of the cylinder past the tip of the pointer in the same direction. Repeat your observations at least three times and determine the time period T. Calcutate G from Eq. 3-4.3.

Experimental results.

Constants of the slide callipers :

Smallest scale div. = ··· mm

··· vern div.s = ··· scale div.s

Vernier constant = 1 sc. div. — 1 vern. div.

= ··· mm = ··· cm

Zero error = ··· mm (add/subtract)

Diameter of cylinder : [(a) and (b) are at right angles.]

No. of obs.		Main Sc. reading in cm M)	Vernier Sc. readiug (V′)	Value of vernier reading V=V′×V.C.	Diameter =M+V in cm	Maen diameter D in cm	Corrected diameter D in cm
1.	(a)						
	(b)						
2.	(a)						
	(b)						
etc.							

M. I. (I) of cylinder :

Mass (M)	Diameter (D)	Radius $R=\frac{1}{2}D$	(I) $=\frac{1}{2} M R^2$
···g	···cm	···cm	···g cm^2

Length l of wire in cm :

Obs.	1	2	3	Mean
Reading	···cm	··· cm	··· cm	··· cm

Constants of the screw gauge :

··· full turns = ··· mm

Pitch (p) = ··· mm

Total circ. div.s = ··· (n)

Least count (p/n) = ··· mm

Zero error = ··· mm (add/subtract)

Diameter d of wire in mm **:** [(a) and (b) are at rt. angles.]

No. of obs.		Linear Sc. reading in mm (L)	Cir. Sc. reading (C)	Value of Cir. Sc. reading V=(C)× l. c. mm	Diameter =L+V in mm	Mean diameter d' in mm	Corrected diameter $d=d'\pm Z$ in mm	Radius $r=\frac{d}{2}$
1.	(a)							
	(b)							
2,	(a)							···mm
	(b)							=···cm
etc.								

Periodic time T **:**

No. of obs.	Time for 30 oscillations in s	Mean time (t) for 30 oscillations in s	Periodic time T
1.	...		
	...	···	$\frac{t}{30}=\cdots$s
3.	...		

Result :

Modulus of rigidity $G=\dfrac{8\pi lI}{r^4T^2}=\cdots$dyn/cm^2.

Method followed : (A short statement)

1. I determined the mass and diameter of the suspended cylinder, and calculated its moment of inertia $I\ (=\frac{1}{2}MR^2)$. I then checked if the suspended system was free to rotate.

2. The length of the experimental wire between the upper and lower points of attachment was measured. The radius of the wire was carefully measured by taking···readings at different places.

3. The periodic time of *torsional oscillations* of the wire was determined from a total of ··· oscillations.

From these data I calculated G.

3-4.1. Oral Questions.

1 and 2. As in Sec. 3-3.1.

3. How do you measure the strain in this case ?

4. What factors control the periodic time of the torsional oscillations of the experimental wire ?

5. What is meant by the *restoring torque per unit twist* ? What factors control this quantity ?

6. Why do you take special care in measuring r and T ?

7. Why is this method called a *dynamical method* ?

8. Distinguish between *pendular* and *torsional* oscillations. What factors control them ?

Answers :

1 and 2. As in Sec. 3-3.1.

3. The strain is not directly measured. It is involved in the calculation of the restoring torque.

4. The moment of inertia of the suspended system and the restoring torque due to the twist of the wire.

5. When a wire is twisted, elastic forces are so set up within the wire as to oppose the twist. These forces constitute a couple, which is known as the restoring couple. The moment of this couple when the twist is one *radian* is known as the retoring torque per unit twist. Its value is determined by the length and radius of the wire and the rigidity modulus of its material (Eq. 3-4.2).

6. G depends on r^{-4} and T^{-2}. The contributions of the relative errors dr/r and dT/T to the relative error dG/G in G are respectively $4(dr/r)$ and $2(dT/T)$. Since r itself is a small quantity the relative error in it is much larger than those in l and I. Hence r requires to be determined with as high a precision as possible. The relative error dT/T also requires to be reduced. Hence T has also to be determined with a high precision.

7. Because the wire under investigation is not in equilibrium during observation.

8. Pendular oscillations are like those of a pendulum. *Gravity controls them.* Torsional oscillations are angular oscillations about the suspension axis. These are controlled by the rigidity modulus.

3-5. To determine the moment of inertia of a body about an axis passing through its centre of gravity

Description of apparatus. In the method described below a simple apparatus is utilised to determine the moment of inertia of a body about an axis which coincides with the axis of suspension of the body.

The apparatus consists of a light symmetrical frame, suspended by means of a wire. Cylinders or rectangular solids can be so placed in this frame that the axis of suspension passes through the centre of gravity of the solid. This frame is called *moment of inertia table.*

The whole apparatus is enclosed in a glass case to protect it from draught.

The time period of torsional oscillations of the suspended system depends on the moment of inertia I_0 of the system about the axis of suspension and on the suspension itself. I_0 may be determined by noting the time period when another body of known moment of inertia about the given axis of rotation is placed on the frame. This body may be one of regular geometrical shape (such as a cylinder), the moment of inertia of which may be found by calculation. When I_0 of the frame is known, the moment of inertia of any other body about the axis of suspension may be found by placing the body on the frame and noting the time period of torsional oscillations. To make sure that the axis about which the moment of inertia is required coincides with the axis of suspension of the m.i. table, the table should be marked with concentric circles and perpendicular diameters.

Theory. Let I_0= moment of inertia of the frame about the axis of suspension,

c=torsional couple exerted by the wire for a twist of one radian (torque per unit twist),

T_0=time period of a torsional oscillations of the frame alone.

Then, the time period of torsional oscillations is

$$T_0=2\pi\sqrt{I_0/c} \qquad (3\text{-}5.1)$$

If I_1 is the known moment of inertia of a body about an axis through its c.g., then, when the body is placed on the moment of inertia table with the suspension axis coinciding with the above axis, the time period T_1 of torsional oscillations is given by

$$T_1=2\pi\sqrt{(I_0+I_1)/c} \qquad (3\text{-}5.2)$$

From equations (3-5.1) and (3-5.2) we get

$$I_0=\frac{T_0^2}{T_1^2-T_0^2}.I_1 \qquad (3\text{-}5.3)$$

The moment of inertia I_2 of the experimental body is obtained by placing it on the moment of inertia table properly and noting the time period T_2.

$$T_2 = 2\pi\sqrt{(I_0+I_2)/c} \qquad (3\ 5.2)$$

Combining equations (3-5.3) and (3-5.4)

$$I_2 = \frac{T_2^{\,2} - T_0^{\,2}}{T_1^{\,2} - T_0^{\,2}} . I_1 \qquad (3\text{-}5.5)$$

Thus measuring T_0, T_1 and T_2 and knowing I_1, I_2 may be found out.

If the body of known moment of inertia is a right circular cylinder of mass m and radius r, moment of inertia I_1 of the cylinder about its own axis is given by $I_1 = mr^2/2$. We shall call it the *test cylinder*. [If the same cylinder is so placed that the axis of suspension passes through its c.g. and perp. to its own axis then $I_1 = m\left(\frac{l^2}{12} + \frac{r^2}{4}\right)$ where l is the length of the cylinder.]

List of apparatus. Moment of inertia apparatus ; test cylinder ; body under investigation ; stop-watch ; slide callipers.

Instructions. Make sure that the suspended table is horizontal. Twist the suspended system through an angle and allow it to make torsional oscillations. Damp out pendular oscillations of the frame, if there be any, by lightly touching the wire near its lower end by means of a soft felt or cotton pad.

(2) Measure the time for thirty oscillations or more, three times, by means of a stop-watch. For this purpose, observe transits of some fixed vertical line on the frame in the same direction across a pointer placed against its position of rest. This reduces observational error.

(3) Place the given cylinder of known or calculable moment of inertia on the frame and adjust as best as you can as that the axis of the cylinder is coincident with the axis of suspension and the centre of gravity of the cylinder also lies on it. Measure the time for thirty oscillations, or more, three times as before.

(4) Remove the cylinder from the frame and place the experimental body on it so that the axis, about which the moment of inertia is to be determined, is coincident with the axis of suspension. Measure the time of thirty oscillations or more, three times.

(5) Measure the mass m of the cylinder by means of a balance correct to three significant digits only and the diameter of the cylinder by means of a pair of slide callipers.

Experimental results :

(It is assumed that the moment of inertia of the test cylinder is to be determined from measurements.)

Constants of the slide callipers :

(Enter as in Expt. 3-4.)

Diameter of the test cylineder :

(Enter as in Expt. 3-4.)

Moment of inertia I of the test cylinder :

(Enter as in Expt. 3-4.)

Time periods :

Load on the frame	Time for 30 oscillations	Mean time for 30 oscillations	Time period
Nil	(*i*) ··· s (*ii*) ··· „ (*iii*) ··· „	············ s	······ s (T_0)
Cylinder (of known moment of inertia)	(*i*) ··· s (*ii*) ··· „ (*iii*) ··· „	············ s	······ s (T_1)
Experimental body	(*i*) ··· s (*ii*) ··· „ (*iii*) ··· „	············ s	······ s (T_2)

Result. The moment of inertia I_2 of the body about the given axis passing through its centre of gravity is given by

$$I_2 = \frac{T_2^2 - T_0^2}{T_1^2 - T_0^2} \cdot I_1 = \cdots\cdots\cdots \text{g cm}^2.$$

Method followed : (A brief statement)

1. I checked whether the suspended table (cradle) on which the bodies would be placed was horizontal. It was then allowed

to execute free torsional oscillations. The periodic time T_0 was found out.

2. The moment of inertia of the test cylinder about its own axis was found out by measurement.

3. The test cylinder was placed on the cradle with its *long axis along the axis of suspension.* Its periodic time T_1 for torsional oscillations was then determined.

4. The test cylinder was replaced by the body under investigation. The axis about which its moment of inertia was to be determined, was made to coincide with the axis of suspension of the cradle. The periodic time T_2 for torsional oscillations was then determined.

5. From the data so obtained the required quantity (I_2) was calculated.

Precautions. Take care to damp out pendular oscillations of the system, if any, before measuring time. (In measuring time of oscillations, the amplitude may be relatively large.)

Unless the suspension axis passes through the c.g. of the body, the observed moment of inertia will be higher.

If the oscillating system has no glass cover, see that the system is not disturbed by air currents.

3-5.1 Oral questions.

1. Define moment of inertia.
2. Why is it necessary to mention the axis in the definition ?
3. What is the radius of gyration ?
4. Distinguish between torsional and pendular oscillations. Are the time periods of the two governed by the same factors ?
5. About which axis have you found out the moment of inertia of the experimental body ?
6. What is the most serious source of error in this experiment ?

Answers :

1. Moment of inertia I of a *body* about any *axis* is the sum of products of the mass dm of each element of the body and the square of r, its distance from the axis. $I=\Sigma r^2 dm$. When a couple is applied so as to cause a body to rotate about an axis, the ratio of the moment of the couple to the angular acceleration produced, is the moment of inertia of the body about the axis.

2. For different axes, the same body has different moments of inertia.

3. The moment of inertia I of a body of mass M about an axis may be expressed in the form $I=Mk^2$. k is called the radius of gyration of the body about the given axis. So far as rotation of the body about the given axis is concerned, we can replace the extended body by a point particle of the same mass M, placed at the distance k from the axis. k depends on the position of the axis.

4. See answer to Q. 8. Sec. 3-4.1.

5. (Say which axis, if it is mentioned in your question.)

6. To make the given axis of rotation of the body coincide with the axis of rotation of moment of inertia table. (Unfortunately, there is no simple way of doing it.)

3-6. To measure the surface tension of water with the help of capillary tube

Theory. When a capillary glass tube of *uniform circular section* stands vertically in water, water rises in the tube to a certain height, say h, above the free surface of the liquid. If r is the internal radius of the tube and ρ the density of water, then the surface tension γ of water is given by

$$\gamma=\tfrac{1}{2}r\rho g\,(h+\tfrac{1}{3}r) \tag{3.6.1}$$

where g is the acceleration due to gravity.

List of apparatus. Supplied capillary tubes ; reference pin ; water vessel ; plane glass strip ; two adjustable clamps ; plumb line ; travelling microscope ; small table of adjustable height to support the water vessel ; a pipette ; spirit level, thermometer.

Instructions. (1) You may be given three or four capillary tubes to work with. (Let us assume you are given three.) The inside and outside of the tubes must be *absolutely free from grease.* Holding them with the fingers may contaminate the outside with grease. So better use a clean piece of linen to handle them. Making the interior really free from impurities, particularly grease, is a real stiff job. You cannot properly be expected to make the inside grease-free. In such a circumstance, the best thing to do is to seek the teacher's advice. Whatever you do, the inside may have some grease contamination. This will give you a much lower value of surface tension than the standard one. You should be prepared for it.

(2) Mount the tubes on the glass strip so that they are parallel to each other and project equally on one side of the strip (Fig. 3.6).

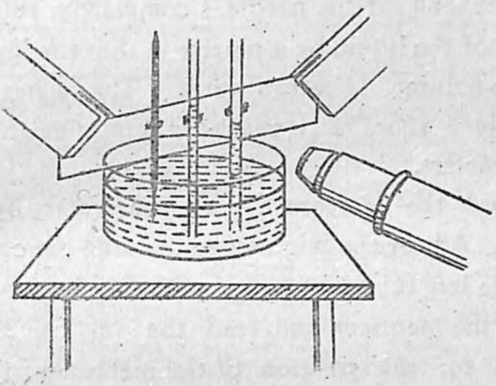


Fig. 3.6

Fix them on the strip by a drop or two of wax on each. The distance separating one tube from the other should be at least two centimetres. Similarly, mount the needle pointer *of known length* parallel to the tubes so that its fine end projects a little less than the projected ends of the tube (See Fig. 3.6).

(3) Hold the glass strip, with the tubes in a vertical plane, by two clips on stands. Check against a plumb line and make sure that the needle and the tubes are vertical.

(4) Suitably place a microscope so that its horizontal traverse is parallel to the plane of the glass plate. Level the bed of the microscope with a spirit level and make the axis of the microscope horizontal. *Focus the eyepiece on the cross-wires.*

(5) If the length of the pointer is not known, focus the microscope on the lower tip of the pointer. Raise the microscope vertically and make sure that it reaches the upper end of the pointer. If the two ends are not on a vertical line, slightly rotate the glass strip in its own plane till they are so. Take the readings on the vertical scale of the microscope when the images of the lower and the upper tips touch that of the horizontal crosswire.

(6) Place a glass trough free from grease on a stand, the height of which can be adjusted. So place the trough that the lower ends

of the tubes are inside it while the end tubes are at least 2 cm away from the edge of the vessel. Pour the water into the vessel till the lower end of the needle is completely submerged. Then remove some of the liquid by a pipette so that the liquid just touches the tip of the pointer. Use tap water. The water will now rise in the capillary tubes and reach different heights if they are of different diameters.

(7) Record the temperature of the water by means of a thermometer. Adjust the microscope to bring the concave meniscus of the extreme left tube into focus. Set the horizontal cross-wire tangential to the meniscus and read the vertical scale. Similarly take readings for the position of the meniscus in the other tubes as well as for the top end of the pointer. Note the temperature of the water again.

(8) Hold the glass strip carrying the tubes in a horizontal plane such that the lower ends of the tubes face the microscope. Focus the microscope on an end. The circular cross-section of the bore of the capillary will be visible. Measure the horizontal and vertical diameters of the inner circle of the tubes, that is, of the bore of the capillary. Take at least two readings of each.

Experimental results :

Constants of the travelling microscope :

Smallest scale div. = ··· mm

··· vern. div.s = ··· scale div.s

Vernier constant = 1 sc. div. − 1 vern. div.

= ··· mm = ··· cm

(The vernier constant was the same on the horizontal and vertical scales.)

Length L of the pointer.

No. of obs.	Readings in cm. of						L in cm A ∼ B	Mean L in cm
	Lower end			Upper end				
	M.S.	V. S.	Total (A)	M. S.	V. S.	Total (B)		
1.							···	
2.							···	
3.							···	

Temperature of water (°C)..

Initial	Final	Mean
...	...	...

Data for h.

Tube no.	Readings for the concave meniscus in cm			Readings for the top end of the pointer in cm			$A \backsim B$ $=C$ in cm	Height of the liquid column $h=L-C$ in cm	Mean h in cm
	Main scale	Vernier	Total (A)	Main scale	Vernier	Total (B)			
I	...	...	...				...	...	
				...	...	...			
	...	...	...				...	...	
II	...	...	...				...	...	
etc.	...	...	...	...	...	...	...	...	

Radius of the tube (r).

[(a) and (b) readings for horizontal and vertical diameters]

Tube	Obs	Readings in cm. of Left or the lower end			Readings in cm. of Right or the upper end			Diameter $C \backsim D$ in cm	Mean diameter in cm	Mean radius, (r) in cm
		Main scale	Vernier	Total (C)	Main scale	Vernier	Total (D)			
I	1. (a)								...	...
	(b)									
	2. (a)									
	(b)									
II etc.	1. (a)									
	(b)									
	2. (a)									
	(b)									

Result:

Tube No.	Height h of liquid column	Radius r of the tube	$h \times r$	Surface tension $\gamma=\frac{1}{2}r\rho g(h+\frac{1}{3}r)$	$\frac{1}{r}$ in cm^{-1}
	... cm	... cm		... dyn/cm	
II	... cm	... cm		... dyn/cm	
etc.	etc.	etc.		etc.	

Mean $\gamma = \cdots$ dyn/cm

$\therefore$ Surface tension of water at ··· °C = ··· dyn/cm.

Jurin's law and graphs.

When a liquid rises in a capillary tube, Eq. 3·6.1 shows that the product hr is constant for a given liquid. This relation is known as Jurin's law. It is true if we ignore the volume of the meniscus.

From observations it is found that the product $h \times r$ is constant within the limits of the experimental error. Hence Jurin's law is verified.

Jurin's law can also be verified graphically. If we plot r along X-axis and h along Y-axis and if the nature of the graph is a rectangular hyperbola, the Jurin's law is true. We can also plot h vs $1/r$. In that case the graph will be a straight line passing through the origin.

Method followed : (A brief statement)

1. The given capillary tubes and the needle pointer were mounted parallelly on a strip of glass at distances of 2 cm and fixed to the strip with wax. The lower end of the needle was about 1 cm above the lower ends of the tubes.

It was assumed that the given tubes were grease free, particularly the inside. The tubes were handled with a clean piece of linen. *They were not touched by the fingers.*

2. The glass strip was held horizontally by two clamps, the tubes and needle being vertical. The empty water vessel was placed on an adjustable table below the tubes. Water was poured into it so that the level just reached the lower end of the pointer.

3. A travelling microscope was set up with its horizontal travel parallel to the glass strip. Its vernier constants were determined.

4. Readings were then taken of the various quantities as recorded under 'Experimental results' and the final result calculated.

Precautions. (*i*) The greatest precaution had to be taken to avoid grease contamination of the water and the inside of the capillary. Complete removal of grease is a highly complicated and long process. So I had to *assume* that the water vessel and the supplied tube were grease free. I took particular care not to contaminate them in any way, and handled them with a clean piece of linen without touching them with my fingers.

(*ii*) Close to an obstruction, water rises along it. So I kept a distance of about 2 cm between the walls of the vessel and the tubes and pointer.

(*iii*) It is somewhat difficult to judge when the water just touches the pointer. Adjustment was made by keeping the level a little low initially and then adding water drop by drop from a pipette. The lower ends of the capillary tubes were at least 1 cm within the water.

[**Remarks.** It is extremely difficult to avoid grease contamination. The student cannot be expected to take effective steps to remove grease contamination from inside the capillary or from the water vessel. *They should be supplied with grease free material.* Fresh capillary tubes of diameter about 2 mm will be suitable. h will be around 2 cm. Assuming grease free conditions, relative error in the result will be limited by that in r. With r 1 mm, dr/r may be greater than 2%. For a 1 mm bore of the capillary dh/h will be about 10 times less.

Note on cleaning grease. To be reasonably sure that the capillary is free from grease, it should be immersed in strong chromic acid for 24 hours and successively treated with nitric acid, caustic soda and tap water.

A capillary tube drawn from melted glass tube is reasonably free from grease as heat burns it out. But a tube drawn by a beginner will be too oval for work.]

3-6.1. Oral questions.

1. Define surface tension. What is the unit in which it is expressed ?
2. Is there any tangential force on the surface of the liquid ?
3. Where does this force come from ?
4. What is the effect of temperature on surface tension ?

5. When does surface tension vanish ?
6. Define angle of contact. What is the value of the angle of contact between water and glass ?
7. What causes the liquid to rise in the capillary ?
8. Why is mercury depressed ?
9. Is it proper to measure the radius of the capillary at one end ? Why do you take two readings at right angles ?
10. If your vernier reading is in error by 0·02 mm what is the percentage error in the value of the radius of the narrowest tube you have used ? What is the percentage error in the shortest height you have measured of the rise ?
11. Say from the above if it is more profitable to use wider tubes.

Answers.

1. The free surface of a liquid behaves like a stretched membrane. It tends to contract. The tangential force acting across unit length of the surface is called the *surface tension*. It is measured in *dynes per centimetre* in cgs units, or in newtons per metre in SI units.

2. A free surface of a liquid is under a state of tension, causing a tendency for the portions of the surface to seperate from each other. This is clearly seen when a liquid film is punctured. So there are tangential forces acting on the surface.

3. The tension is an effect of the *forces* of attraction existing between the *molecules* of a liquid (forces of cohesion).

4. Increase of temperature reduces surface tension.

5. At the *critical temperature*.

6. When a liquid meets a solid the angle between the solid and the tangent line to the liquid surface, measured in a vertical plane *within the liquid*, is called the angle of contact.

Briefly speaking, it is the angle at which a liquid meets a solid.

7. It is the force of attraction between the solid and the liquid molecules (force of adhesion). When the effect of the force of adhesion exceeds the effect of the force of cohesion the liquid rises.

8. Mercury has a strong cohesive force. Its effect in reducing the area of the free surface cannot be counterbalanced by the adhesive force. Hence mercury is depressed in a glass tube.

9. According to theory r in the formula is the radius of the capillary at the point up to which the liquid rises. Properly speaking, we should cut the tube at that place and measure the diameter there. This will make the tube useless for a later use. Assuming that the diameter is uniform we measure that at the end.

Two readings at right angles are taken to reduce the effect of any ovalness of the cross section of the tube. If the two readings differ by 5% or more, the advice is to reject the tube.

10. If the radius of the narrowest tube is 1 mm, the percentage error is (0.02 mm/1 mm)×100=2 (2%). The height of ascent in this case will be about 1.5 cm. The percentage error will be (0.02 mm/15 mm)×100=about 0.1 (0.1%).

11. It is better to use wider tubes (See also 'remarks' at the end of Sec. 3-6.)

3·7. To determine the viscosity of water by its rate of flow through a capillary tube (Poiseuille's method)

Description of apparatus. The arrangement of apparatus for this experiment is as shown in Fig. 3.7. A is a constant level tank from which water is allowed to flow through the horizontally held capillary tube C. Water enters the tank from a suitably placed larger tank whose temperature should be steady. To ensure a steady surface the inflow of water into the tank is adjusted by means of pinch-cock to be slightly in excess of the outflow through the capillary tube. The excess of water then flows out in a thin stream into the sink through the middle tube B. A cathetometer

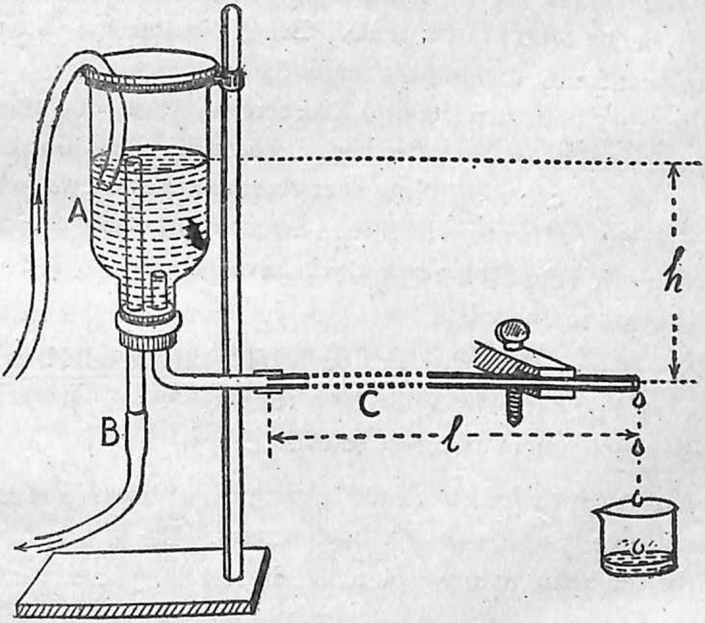


Fig. 3.7.

is used to measure the height of water surface in the tank A above the outflow end of the capillary tube C. (For description and adjustments of the cathetometer see sec. 2-6.)

In using the cathetometer (Sec. 2-6) care must be taken to ensure that

(1) The rod AB (Fig. 2.8) is truly vertical ;

(2) The axis of the telescope is horizontal ;

(3) The object is accurately focussed on the cross-wires.

The **necessary adjustments** are as follows :

(*a*) Turn the rod AB till the telescope is parallel to the line joining two of the levelling screws of the base. (Some cathetometers have two adjustable screws, the third leg being supported on a pin of fixed height. In such cases, the line to which the telescope is set parallel should pass through the fixed pin and any other screw.) The bubble of the spirit level will generally be found to be away from the centre of its scale. Bring the bubble *halfway* back to the centre by turning the screw F.

For the other half turn the two base screws (those mentioned) by equal amounts *in opposite directions* at the same time until the bubble reaches the centre. (Note that these are the screws which form the imaginary line to which the telescope axis was set parallel. If, instead of two adjustable screws, you have a fixed pin and one screw, turn that screw only.)

(*b*) Next rotate the rod AB through 180°. If the bubble is not at the centre, bring it halfway back by the screw F and the other halfway by the previous two base screws.

(*c*) Now turn the rod until the telescope is at right angles to the previous line joining the two base screws. Bring the bubble back to the centre by turning the remaining levelling screw at the base.

In general it will be necessary to repeat the adjustments (*a*), (*b*), (*c*) several times. The bubble will finally remain in the centre, whatever the direction in which the telescope is turned.

Theory. Let a liquid be allowed to flow in stream lines* through a horizontal capillary tube of internal radius r and length l. Assuming that the liquid moves *without appreciable kinetic energy*, the volume V of it which flows out in time t under a steady difference of pressure P across its ends is given by.

$$V=\frac{\pi P r^4 t}{8l\eta}$$

$$\text{or,}\quad \eta=\frac{\pi P r^4 t}{8lV}=\frac{\pi P r^4}{8lQ} \tag{3-7.1}$$

where η is the coefficient of viscosity of the given liquid, and Q its *rate of flow*.

List of apparatus. Viscosity apparatus ; capillary flow tube ; clamp for holding it horizontally ; graduated measuring cylinder (of say 250 cm^3 capacity) ; beaker ; travelling microscope ; cathetometer : stop-watch ; metre scale.

Instructions. (1) Take a capillary tube 1-2 mm in diameter and 40 to 50 cm in length. Clean it by passing dilute nitric acid and then a strong solution of caustic soda. Finally tap water to flow through it for about five minutes. Dry it by passing hot air through it.

(2) Mount the tube horizontally and measure the diameter of the capillary *at both ends* with a travelling microscope. Take at least six readings at each end, turning the tube by 60° at a time.

(3) Measure the length of the capillary tube directly by means of a metre scale.

Taking Reynolds number (N) as 2000, and substituting values in the equation $v_c=N\eta/\rho d$, we find that for water at 20°C ($\eta=0{\cdot}01$ poise) and a tube diameter (d) of 0·2 cm, $v_c=1$ m/s. The velocity of flow through the capillary is much smaller under reasonable laboratory conditions. Hence the flow is stream-line.

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*The relation 3-7.1 holds only when the flow of liquid is in stream lines. For capillary tubes, the limiting pressure which causes turbulent motion is so high that for all ordinary differences of pressure the flow may be taken to be in stream lines.

Having found r and l, arrange your apparatus as shown in Fig. 3.7.

(4) Set up the cathetometer (vide § 2-6) at a distance and level it so that the pillar is vertical and the telescope axis horizontal. Find the vernier constant of the cathetometer scale.

(5) Focus the cross-wires on the axis of the outflow end of the capillary tube and read the vernier and the main scale. Raise the telescope and focus it on the surface line of the liquid in the constant level tank and again read the vernier and the main scale. Thus get the difference of pressure between the ends of the capillary tube in terms of the height (h) of the liquid column. Take at least two sets of readings to guard against gross error.

(6) Record the temperature of the liquid in the constant level tank. As the capillary tube is horizontal, the liquid issuing out of the tube may run a little back along the under surface of the tube making its collection difficult. In order to eliminate this difficulty, smear a little vaseline on the under surface of the tube near the open end taking care not to contaminate the bore through which the liquid is issuing out.

(7) Allow water to flow out of the capillary for some time into a beaker. When conditions appear steady, place the measuring cylinder to collect water issuing out of the capillary tube and simultaneously start a stop-watch. When about 200 cm^3 have been collected, remove the measuring cylinder and stop the watch. Also stop the flow of water into and out of the tank.

Note the time of flow and the volume of water collected.

(8) Change the height of the liquid by changing the level of liquid in *A*. Take at least three sets of readings at different pressures.

(9) Calculate the value of η by using Eq. 3-7.1 for each set of readings. Also calculate η by drawing h vs V graph. Record your data as follows.

Experimental results :

Constants of the travelling microscope.

Smallest scale div.=···mm

···vernier div.s=···scale div.s

Vernier constant=···1 sc. div. − 1 vern. div.

=···mm=···cm.

(Both horizontal and vertical scales had the same constant.)

Diameter and radius (r) of the capillary bore.

[(a), (b) and (c) are readings for diameters at 60°.]

		Readings in cm of								
		Left end			Right end					
End	Obs.	Main scale	Vernier	Total (A)	Main scale	Vernier	Total (B)	Diameter $(A \sim B)$	Mean diam	Mean radius r
I	(a) (b) (c)								...cm	...cm
II	(a) (b) (c)									

Length l of the capillary glass tube.

(The metre scale was placed at random)

	Left end cm	Right end cm	l in cm	Mean l
1				...cm
2				
3				

Constants of the cathetometer.

(Tabulate as for the travelling microscope)

Constant height h of the water column providing the pressure P.

	Cathetometer readings in cm on										
	Water level in tank			Axis of outflow end							
No. of obs.	Main scale	Vernier	Total (C)	Main scale	Vernier	Total (D)	h $(C \sim D)$ cm	Mean h in cm	Pressure p dyn/cm²	Volume of water Collected V cm³	Time of Collection in s
1 (a)											
(b)											
2 (a)											
(b)											
etc.											

(I took ρ = density of water = 1 g/cm^3 and g = 980 cm/s^2.)

Temperature of the tank water.

Initial temp. = ···°C ; Final temp = ···°C ; Mean temp. = ···°C.

Calculations : Substituting values in the Eq. $\eta=\frac{\pi P r^4 t}{8lv}$, I find that

(*i*) η = ···poise

(*ii*) η = ···poise

(*iii*) η = ···poise

Mean η = ···poise

Result : The viscosity η of water at···°C is

η = ···poise.

(Poise is the unit of viscosity in cgs units.)

Method followed : (A short statement)

1. I cleaned and dried the capillary tube, measured its length and also its diameter at both ends.

2. The apparatus was then set up and the tube attached to it horizontally.

3. The height of the water level in the tank was so adjusted that water came out of the capillary in drops (not in continuous stream).

4. The cathetometer was set up. The vertical distance between the constant water level in the tank and the centre of the outflow end of the capillary tube was mearsured with its help.

5 When conditions were steady, ···cm^3 of water were collected in a measuring cylinder in ···seconds. The temperatures of the water before and after the collection were noted. The mean value was taken as the temperature of the flowing water.

6. Three sets of readings were taken at different pressures.

7. From the data so obtained, η was calculated, in each case.

Precautions. (*i*) In the working formula, the radius of the bore of the capillary occurs in the *fourth power*. Besides r is a small quantity, of the order of 1 mm. The reltive error in r is therefore large, and its contribution to the relative error in η is *four times* dr/r. The radius was therefore measured very carefully and quite a large number of readings was taken to keep dr/r as low as possible.

(The relative errors in P, t, l and V were much smaller and roughly of the same order of magnitude among themselves.)

(*ii*) The mean temperature of the flowing water was noted as viscosity varies rapidly with temperature.

(*iii*) Except during collection, the water coming out of the capillary was held in a beaker so that it may not collect on the table or floor to soil it.

Remark. Viscosity of water at 25°C is about 0·009 poise, at 30°C, 0·008 poise and at 40°C, 0·065 poise. (See table in the Appendix.)

3·7.1 Alternative Method

An alternative arrangement is as shown in Fig. 3.8. The capillary tube C is horizontal and is connected to two small chambers A and B, each of which has two more openings. D is a bottle containing water and is connected to A as shown. E and F are

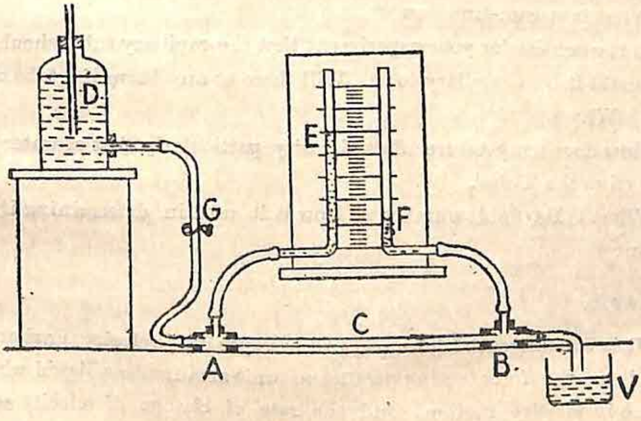


Fig. 3·8

two limbs of a manometer connected respectively to A and B. G is a pinch-cock which can regulate the flow of water. The exit tube for water, which is of india-rubber, should be constricted by a pinch-cock if the water level in F is not visible.

D has a closed air-tight rubber stopper through which a piece of glass tube passes. The lower end of this tube should reach a point will below the surface of water in D. Air bubbles enter D through this tube as water flows out of D. The lower end of the glass tube in D remains at atmospheric pressure Hence the manometer maintains a uniform difference of level until the water in D falls below the lower end of the tube.

The difference of pressure (P) between the two ends of the capillary is obtained from the difference in water levels between E and F.

The procedure is the same as previously described, except that h may be measured from the scale provided with the manometer. h should be noted from time to time to make sure that it is steady. The volume of the collected water is found with the graduated measuring cylinder.

3-7.2. Oral questions.

1. Define coefficient of viscosity. What is viscosity due to ?

2. What do you understand by the term velocity gradient ?

3. What is stream-line flow ?

4. Is it essential for your experiment that the capillary tube should be horizontal ? Should it be a capillary too ? Will there be any harm if a tube of wide bore is used ? Why ?

5. How does temperature affect viscosity, particularly that of water ?

6. Define the 'Poise'.

7. What is Reynolds number ? How is it used in determining if the flow is streamline ?

Answers.

1. It is the tangential force per unit area per unit velocity gradient. In other words, it is the force acting parallel to unit area inside a liquid when the liquid layers are in relative motion, and the rate of change of velocity at the layer in question is 1 cm/s per unit distance normal to the plane.

It is due to transfer of momentum from a faster moving layer to a slower moving layer. The effect is to slow down faster layers and speed up slower layers.

2. If there is relative motion between parallel layers and dv is the difference of velocity between two parallel layers a small distance dz apart, then the quantity dv/dz is called the *velocity gradient* at the layer. It is the rate of change of velocity perpendicular to any layer under consideration.

3. Fluid motion which can be described in terms of stream lines is called *stream-line flow.*

A stream line in the field of motion of a fluid is such a line in the field that the tangent to the line at any point gives the direction of motion of the fluid particle at the point. (It is similar to eletric or magnetic lines of force.)

4. Yes, Poiseuille's equation was established on this assumption. If the tube, of length l', is vertical (say), then a term $l'g\rho$ is to be added to P in Poiseuille's formula.

The formula assumes that the pressure difference P at two ends of the tube is entirely spent is overcoming the viscous forces between the moving layers. No part of it should be spent in giving the liquid kinetic energy. In a tube of wide bore it is not possible to fulfil these conditions.

5. In all liquids, viscosity diminishes with rise of temp. In oils, the change is very rapid. In water, it is about 0·9 centipoise (10^{-2} poise ; cP) at 25°C and 0·8 cP at 30°C. (See 'Remark' at the end of Sec. 3-7 or the viscosity table in the Appendix.)

6. The poise is the cgs unit of coefficient of viscosity. It is the force in dynes acting tangentilly on unit area of a liquid layer when the velocity gradient at the layer is 1 cm/s per centimetre.

7. Reynolds number is a dimensionless combination $v\rho d/\eta$ applied to a liquid flowing through a cylindrical tube, when v = velocity of flow, ρ = density of liquid, d = diameter of the tube and η = coefficient of viscosity of the liquid. Experiment shows that so long as this number is 2000 or less the velocity is streamline.

Test yourself.

1. Why should r (the raidus of the tube) be determined with particular care, and a large number of readings taken ?

[*Hint* : See under 'Precautions (i).]

2. If all the readings of r are the same, what does it mean ? What will be the number of significant figures in your result then ?

[*Hint* : It means that the random errors are 'scale-limited', that is, less than one smallest scale division. See Sec. 1-5 and 1-5.1]

3. What is the number of significant digits in your result ? If this is to be increased, what should be your advice ?

CHAPTER 4

HEAT

4-1. To measure the coefficient of linear expansion with a travelling microscope

[**Description of apparatus**. The experimental material is taken in the form of a tube, about one metre long and 3-4 cm in diameter. It should be covered all over with felt except for a small portion at each end, which should be bare. A very fine line perpendicular to the axis of the tube is ruled on each of these bare portions (Fig. 4.1). They serve as fiducial marks between which the expansion is measured. The tube rests on two V-grooves fixed to a table. Each end of the tube is closed by a tight-fitting cork through which passes a thermometer and a glass tube for admitting steam. The steam leaves through a short tube soldered near about the middle of the experimental tube and is condensed into a vessel containing water.

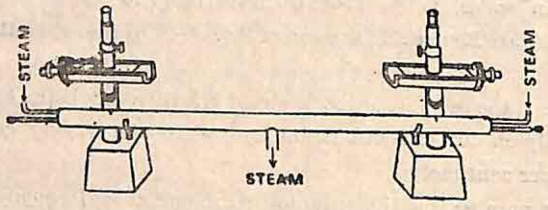


Fig. 4.1

Two low-power microscopes are fixed on the table near the ends of the tube. They can be moved by micrometer screws in a direction parallel to the axis of the experimental tube. The microscopes are provided with cross-wires in the focal plane of the eyepiece and are used for measuring the expansion.]

Theory. If l_1 and l_2 are the lengths of a rod at temperatures t_1°C and t_2°C respectively, then mean coefficient of linear expansion of the material of the rod between the above temperatures is defined by the relation

$$a=\frac{l_2-l_1}{l_1(t_2-t_1)} \text{ per } ^\circ\text{C}$$

A tube behaves as a rod so far as expansion is concerned. It expands in all dimensions with rise in temperature.

List of apparatus. Expansion apparatus fitted with two travelling microscopes ; two thermometers ; boiler, burner, rubber tubes ; metre scale.

[**Instructions**. (1) Measure with a metre scale the distance (l_1) between the two lines on the tube at the room temperature. If necessary, use a rod with two sliding pointers for measuring this length.

(2) Insert a thermometer each at both ends of the tube through the hole in the corks. Push each well into the tube, but see that the mercury meniscus is yet visible and the thermometer scale is in a readable position. Connect the experimental tube by rubber tubes to the boiler and the exhaust for inlet and outlet of steam. Take the readings of both thermometers. The mean of their values is taken as the initial temperature (t_1°C).

(3) Determine the least count of the micrometer scales.

(4) Focus the eyepiece of each micrometer on its cross-wires. While doing so use the eye without accommodation (*i.e.*, look into the microscope as if you want to see something at a long distance). Bring one of the microscopes near to the centre of its range of motion. If necessary, push the experimental tube slightly to bring the fiducial mark at this end in the field of view of this microscope. Focus the microscope on the mark and bring the junction of the cross-wire into coincidence with it. See that there is no parallax between the cross-wire and the image of the mark. Take the micrometer reading. To avoid *error due to back-lash* of the micrometer screw, the microscope should be moved outwards (*i.e.*, towards the end of the tube) while setting the cross-wire on the mark.

Focus the other microscope on the reference line at the other end in a similar way; but in doing so *do not displace the experimental tube in any way.* Take the micrometer reading.

(5) Heat the boiler and allow steam to enter both ends of the tube freely. After you see steam coming out of the exhaust, read both thermometers of intervals of 5 minutes. The heating of the tube increases its length. The marks are therefore displaced away from their positions. When you find that the temperatures have been steady for 10 minutes, read both thermometers. The mean of their values is the final temperature t_2. Then slowly turn the micrometer at one end outwards until the cross-wire is again coincident with the image of the mark. Take the micrometer reading. Do the same thing at the other end.

Turn off the gas under the boiler.]

Experimental results :

Initial length of the rod (l_1). (Scale placed at random)

Obs.	Left end cm	Right end cm	Length cm	Mean l_1
1				
2				
3				...cm

Constants of the micrometer.

Smallest scale div. = ···mm
... full turns = ···mm
Pitch (p) = ···mm
Total circ. div.s = ···(n)
Least count (p/n) = ···mm

(Both micrometers have the same constants.)

Micrometer readings.

Micrometer	Micrometer readings in mm						Diff. of readings	Expansion of the tube $(l_2 - l_1)$
	Initial			Final				
	L. S.	C. S.	Total	L. S.	C. S.	Total		
Right			… (a)			… (c)	$X =$ $(a) \backsim (c)$ = . mm = .. cm	$X+Y$
Left			… (b)			… (d)	$Y =$ $(b) \backsim (d)$ = .. mm = cm	= …cm

Readings of the thermometers.

	Initial °C	Mean initial temp (t_1)	At intervals of 5 minutes during heating in °C						Steady value	Mean final temp (t_2)	Temp, rise $(t_2 - t_1)$
Right Left		.. °C							…°C …°C	…°C	…°C

Result. Mean coefficient of expansion between … °C (initial temp.) and … °C (final temp.)

$$= \frac{l_2 - l_1}{l_1(t_2 - t_1)} = \cdots \text{ per } {}^\circ\text{C}.$$

Method followed.

(1) I measured the distance between the two reference lines on the experimental tube near its ends and below the microscopes.

(2) The apparatus was fitted up and the initial temperatures noted.

(3) The micrometer constants were determined, and the micrometer readings corresponding to the reference lines taken.

(4) Steam from the boiler was allowed to pass through the metal tube. Readings of the thermometers were taken every 5 minutes until they were steady. The steady temperatures were recorded.

(5) Each microscope was again focused on the reference line under it and the new position of the line noted from the micrometer.

(6) From the data so obtained the result was calculated.

Precautions. 1. Back-lash of the micrometer screw must be avoided. For this purpose the microscpe was always made to move outwards in setting the cross-wires on the mark.

2. Sometimes steam does not enter freely at both ends. The reason may be that the inlet pipe at one end has sagged, there-by allowing steam to condense there and choking the pipe. The inlet pipes were therefore so connected that they gradually sloped down from the boiler to the inlet ends.

3. After the initial reading of a microscope had been taken, the experimental tube was not disturbed in any way.

4. Care was taken that the water in the boiler was enough to last the experiment.

Oral questions.

1. Define the coefficient of linear expansion.

2. Why do you call your result the *mean coefficient of expansion* ?

3. If you measured the lengths in inches, would the value of the coefficient come out different ? Would it be the same if the temperature were measured in °F ?

4. If the tube were solid, would you get the same value of a ?

Answers.

1. The coefficient of linear expansion of a material is the expansion per unit length of it for 1° rise of temperature.

2. When the expansion per unit length is measured between two temperatures a fair distance apart, the coefficient is called the mean coefficient between those two temperatures. The increase per unit length per unit rise of temperature is not constant throughout the temperature scale.

3. The coefficient involves the ratio of the increase in length to the original length. Hence if lengths are measured in the same unit, the ratio will be independent of the unit of length. The value will be the same whether lengths are measured either in inches or in centimetres. But the value will depend on the temperature. 1°F is $\frac{5}{9}$ of 1°C. So 1° F will cause less expansion and a will be less.

4. A body, whether solid or hollow, expand in all dimension. Hence a is the same for solid and hollow tubes of the same size.

4-2. To measure the coefficient of linear expansion with an optical lever

Description of apparatus. The experimental material, in the form of a rod (R, Fig. 4.2), stands vertically in a cylindrical tube covered on the outside by felt to prevent loss of heat. This tube has two side tubes for the insertion of thermometers, and two others for inlet and outlet of steam.

The experimental rod projects just beyond the cork at the top of the outer tube. The frame supporting the tube carries a thick glass plate with a hole at its centre. The forward leg of the optical lever (See Sec. 2-7) rests on the top of the experimental rod, while the other two rest on the glass plate. The mirror should have its plane vertical.

A telescope-and-scale is fitted up at a distance of several feet in front of the mirror (See Sec. 2-7).

Theory. If l_1 and l_2 are the lengths of a rod at temperatures t_1°C and t_2°C respectively, then the *mean coefficient* of linear expansion of the material of the rod between the above temperatures is defined by the relation

$$a=\frac{l_2-l_1}{l_1(t_2-t_1)} \text{ per °C} \qquad (4\text{-}2\,1)$$

To measure the increase in length $l_2-t_1=x$ of the rod by an optical lever, let p=length of the arm of the optical lever, d_1 and d_2=the initial and the final values of the scale readings coincident with the cross-wires of the telescope, d= difference of the values of d_1 and d_2, D=distance between the mirror and the scale (measured normal to the mirror).

Then the rotation of the mirror$=x/p$. The angular change of the scale reading is twice this value.

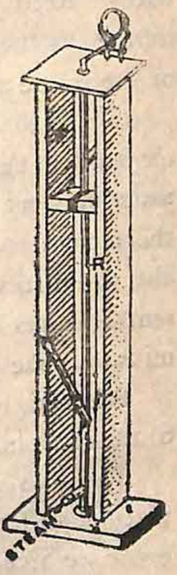


Fig. 4.2

$$\therefore \quad \frac{2x}{p}=\frac{d}{D} \text{ or } l_2-l_1=x=\frac{d}{2D}\times p. \qquad (4\text{-}2.2)$$

List of apparatus. Expansion apparatus ; optical lever ; two thermometers ; metre stick ; diagonal scale ; dividers : telescope-and-scale ; table lamp (with a shade on one side) ; boiler ; burner ; rubber tubes.

Instructions. (1) Take the experimental rod out of the tube and measure its length with a metre scale. Place it in position and insert the thermometers (with their scales in a convenient, readable position). Next, make connections to the boiler.

(2) Place the optical lever in position with its mirror vertical. Arrange the telescope and scale in position. In making the final adjustments (for details see Sec. 2-7), focus the eyepiece on the cross-wires and bring the image of the scale into coincidence with the cross-wires *avoiding parallax.* (The eye should be used without accommodation.) Raise or lower the telescope, or adjust the tilt of the mirror until the cross-wires coincide with the image of a scale reading lying about 5 cm below the centre of the telescope.

(3) Note the scale reading (d_1) which coincides with the cross-wires. Read both thermometers. Their mean value is t_1. (In taking the thermometer readings do not touch the thermometers or the frame supporting the rod, as this may displace the mirror.)

(4) Light the burner below the boiler. *The rubber tube from the boiler to the inlet should go in a gradual slope so that condensed water may not collect in between.* After some time start reading the thermometers at intervals of 5 minutes. As a check note down also the corresponding scale reading on the cross-wires. When the temperatures and the scale reading appear to be steady for ten minutes, take them down as the final values.

Put out the burner. Measure the distance from the mirror to the scale horizontally with a tape.

Take an imprint of the supporting points of the lever on a piece of stiff paper and measure p. (For details of this measurement see Sɘcedj. 2-7. The imprint and the details of construction for finding p are to be record.)

Experimental Results :

Initial length of the rod (l_1).

	(*i*)	(*ii*)	(*iii*)	Mean
$l_1=$	...cm	...cm	...cm	...cm

Temperature record.

		Upper thermometer	Lower thermometer	Scale reading
Initial values		...(t_1')	...(t_1'')	(d_1)
Values during heating (at intervals of 5 minutes)	(i)	...	...	...
	(ii)	...	...	...
	(iii)	...	...	...
Final steady values		...(t_2')	...(t_2'')	...(d_2)

Values for optical lever.

Distance between mirror and scale (D)$=$...cm

Change of scale reading$=d_1 \sim d_2 = d$ $=$...cm

Effective-length (p) of arm of the optical lever (measured with divider and diagonal scale)

	(i)	(ii)	(iii)	Mean
$p=$				...cm

Initial temp. $(t_1)=\frac{1}{2}(t_1'+t_1'')$ $=$...°C

Final temp. $(t_2)=\frac{1}{2}(t_2'+t_2'')$ $=$...°C

Result.

$$l_2-l_1=\frac{d}{2D}\times p=\cdots\text{cm}$$

$$\text{and}\quad a=\frac{l_2-l_1}{l_1(t_2-t_1)}=\cdots\cdots\text{per °C.}$$

Method followed. (1) I measured the length of the experimental rod with a metre scale. It was then placed in the jacket, the thermometers were inserted and the apparatus fitted, connections were made with the boiler.

(2) The optical lever was placed in position and the scale and telescope fitted up in front of it properly.

(3) The initial temperature of the rod was noted. The scale reading (d_1) in the optical lever corresponding to the initial temperature was noted.

(4) Water in the boiler was put to boil. Thermometer readings were taken every 5 minutes until they were steady.

(5) The scale reading (d_2) in the optical lever was noted when the temperature became steady.

(6) The burner was put out. The horizontal distance D between the scale and the mirror of the optical lever was measured with a tape.

(7) The optical lever was now placed on a piece of stiff paper and a sharp imprint of the points of its legs made on it. They formed an isosceles triangle. The height (altitude) of this triangle was measured with the help of a pair of dividers and a diagonal scale reading up to 0·1 mm.

(8) From the data obtained, the value of α was calculated.

Precautions. (*i*) After the initial reading d_1 had been taken the mirror and the telescope-and-scale were not disturbed in any way.

(*ii*) p, the length of the lever arm, was measured carefully as an error in it would cause the largest error in the final result.

(*iii*) Care was taken to see that the rubber tubes from the boiler sloped gradually to the jacket and did not sag much anywhere. Much sagging of any of the tubes will choke it with condensed water, and steam will not pass through it.

Oral questions

1. Explain how the optical lever works.

2. If you have two optical levers, one with a longer arm and the other with a shorter one, which would you prefer for your work ? Why ?

3. What is the magnification produced by the optical lever ? (*Note*—The mangification is the ratio d/x, which is equal to $2D/p$).

Answers 1. (See Sec. 2-7.)

2. The one with the longer arm. x is proportional to the length of this arm (Eq.s 4-2.1 and 4-2.2). The longer the arm the less the relative error in it, and hence in the result

3. (State the value of $2D/p$ from your data.)

4·3. To determine the coefficient of apparent expansion of a liquid by the weight thermometer method

[**Note**. A *weight thermometer* is an instrument for measuring the apparent coefficient of expansion of a liquid relative to a containing vessel by determination of the amount of liquid expelled from the vessel on heating through a measured temperature interval. A *specific gravity bottle* may serve as a useful weight thermometer.]

Theory. If m_1 and m_2 are the masses of the given liquid which fill the vessel completely at temperatures t_1 and t_2 respectively, then the *mean coefficient of apparent expansion* γ_a of the given liquid between these two temperatures is given by

$$\gamma_a = \frac{m_1 - m_2}{m_2(t_2 - t_1)} \tag{4·3.1}$$

List of apparatus. Specific gravity bottle, experimental liquid, thermometer, bunsen burner, tripod stand and wire gauge, water bath, stand, thread, blotting paper, soft dry linen.

Instructions. 1. Take a clean, dry, empty specific gravity bottle (with stopper) and weigh it to the nearest decigram. Fill it with the experimental liquid at the room temperature, stopper lightly, wipe dry and weigh. Note the room temperature.

2. Suspend the bottle in the water bath so that the stopper keeps a little out of the water. Bring the water in the bath slowly to the boiling point and keep the vessel at this temperature for at least 10 minutes. Soak out with a piece of blotting paper the liquid that has come out of the capillary mouth of the stopper.

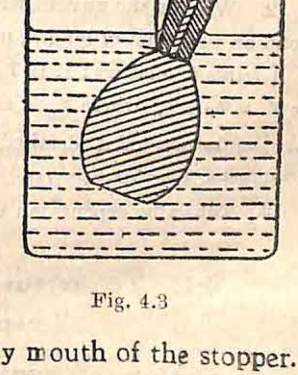


Fig. 4.3

3. Remove the bottle from the bath, wipe it dry and allow it to cool to the room temperature. Weigh it.

Experimental results :

Weight (W_1) of empty vessel

$= \cdots + \cdots + \cdots + \cdots = \cdots$ g

Room temperature (t_1) $= \cdots$ °C.

Weight (W_2) of vessel completely filled with liquid at

temperature t_1 °C $= \cdots + \cdots + \cdots + \cdots = \cdots$ g

Constant higher temperature t_2 at which bath was

maintained $= \cdots$ °C

Weight (W_3) of vessel completely filled with liquid at

temperature t_2 °C $= \cdots + \cdots + \cdots + \cdots = \cdots$ g

∴ Weight of liquid which fills the vessel at

temperature t_2 °C $(m_2) = W_3 - W_1 = \cdots$ g

Weight of liquid expelled when the vessel is heated from t_1 to t_2 °C

[*i.e.*, $(m_1 - m_2)$ of Eq. 4-3.1] $= W_2 - W_3 = \cdots$ g

. . Coefficient of apparent expansion

$$a = \frac{m_1 - m_2}{m_2(t_2 - t_1)} = \frac{W_2 - W_3}{(W_3 - W_1)(t_2 - t_1)} = \cdots \text{ per } ^\circ\text{C}$$

Oral questions

1. Distinguish between the coefficients of true and apparent expansion of a liquid. What are you measuring in this case ? What is the relation between the two coefficients ?

2. What is the unit in which the coefficients are expressed ? Does the value depend on the units of length, mass, volume and tempesature ?

[*Hints to answers* : 1. If γ is the coefficient of real expansion, we ordinarily take $\gamma = \gamma_a + \gamma_v$ where γ_v is the coefficient of volume expansion of the material of the container. But detailed calculation shows that in the case of a weight thermometer $\gamma_r = \gamma_a + (m_1/m_2)\,\gamma_v$.

2. The value depends on the unit of temperature.]

4-4. To measure the absolute coefficient of expansion of mercury

Description of apparatus. A commonly available form is shown in the adjoining figure. The tube containing mercury is bent into the shape of a rectangle, the open ends being brought together near the middle of the upper arm. The longer vertical portions are surrounded by jackets, in which thermometers can be inserted. A jacket should also surround the shorter vertical tubes which are close together. The tubes are mounted on a vertical wooden frame.

For measuring heights, a cathetometer is preferred. If it is not available, a travelling microscope should be used for measuring the difference in level of the mercury at the top. A metre scale may be used for measuring the total vertical height of the colder mercury column. By careful handling the error arising out of the use of a metre scale may be kept within 0·5%.

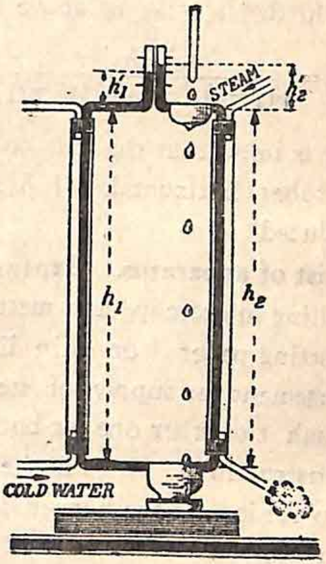


Fig. 4.4

Theory. We assume that the longer cold and hot vertical limbs are at temperatures t_1 and t_2, and their respective heights are h_1 and h_2. Both shorter vertical limbs are assumed to be at the same temperature t_3, while the colder limb has a height h_1' and the warmer, h_2'. The densities of mercury at the three temperatures are respectively ρ_1, ρ_2, ρ_3.

Since the hydrostatic pressure exerted by the hot and cold limbs must be equal, we have

$$h_1\rho_1 g + h_1'\rho_3 g = h_2\rho_2 g + h_2'\rho_3 g.$$

If γ_r is the coefficient of absolute (or real) expansion of mercury, then $\rho_1 = \rho_2\{1+\gamma_r(t_2-t_1)\}$ and $\rho_3 = \rho_2\{1+\gamma_r(t_2-t_3)\}$.

Substituting these values in the former relation, we get

$$h_1\{1+\gamma_r(t_2-t_1)\} + h_1'\{1+\gamma_r(t_2-t_3)\}$$
$$= h_2 + h_2'\{1+\gamma_r(t_2-t_3)\}.$$

If the cross-tubes are horizontal, $h_1=h_2$, then

$$\gamma_r=\frac{h_2'-h_1}{h_1(t_2-t_1)-(h_2'-h_1')(t_2-t_3)}. \tag{4-4.1}$$

If further $t_1=t_3$, the above reduces to

$$\gamma_r=\frac{h_2'-h_1'}{\{h_2-(h_2'-h_1')\}(t_2-t_1)}. \tag{4-4.2}$$

(It is important that the hot and cold limbs be vertical and the cross-tubes horizontal. If $h_1 \neq h_2$, an indeterminate error is introduced).

List of apparatus. Expansion apparatus, cathetometer (or travelling microscope and metre scale), thermometers, two pieces of blotting paper (or thin linen), water dripping arrangement, arrangement for supply of steam through one jacket and water through the other one (or both).

Instructions. 1. Fill the boiler about three-fifths with water and place it over the burner for the water to boil. Connect the boiler to the inlet end of the steam jacket of the apparatus. The exhaust steam should be led into a suitable vessel for condensation.

2. Drip cold water on to the two pieces of blotting paper wrapped round the horizontal limbs near the steam jacket.

3. If your arrangement permits, circulate water from the tap through the other jacket (or jackets, if there is one enclosing the two short upright tubes). If this is not possible, you have to leave these limbs exposed to the air. (In the latter case, you have to take $t_1=t_3=$ room temperature. This may introduce a small error.)

4. If there is provision for inserting thermometers into the jackets, introduce them. Record t_2 at intervals of 5 min. until it is steady. Note t_1 and t_3.

5. Adjust the cathetometer (See Sec. 2-6) so that its pillar is vertical and the telescope axis horizontal. Determine the vernier constant. Use it to measure the heights h_1 and h_2, and also $h_2'-h_1'$, when this difference becomes *steady*.

If no cathetometer is available, use a metre scale for measuring h_1 and h_2 (h_2 for a check). [Measure distances between the axes of the horizontal tubes near the cold limb (for h_1) and those near the hot limb (for h_2). For $(h_2'-h_1')$, use a travelling microscope placed on a suitable platform and properly levelled.]

Use formula 4-4.1 or 4-4.2 as may be applicable. (The table below is drawn up for $h_1=h_2$ and $t_1=t_3$.)

Experimental results :

Determination of vernier constant :

Smallest scale div.=···mm

···scale div.=···vernier div.

∴ Vernier constant = 1 scale div. − 1 vern. div.

=···mm=···cm

Telescope readings :

Readings of Mercury in cm.																Hight of the cold column $h_1=(b)-(a)$ cm	Expansion $h_2'-h_1'=(c)-(d)$ cm
On the axes of								Meniscus of (steady value)									
Lower tube (a)				Upper tube (b)				cold limb (c)				hot limb (d)					
M.S.	V.S.	Total	Mean	M.S.	V.S.	Total	Mean	M.S.	V.S.	Total	Mean	M.S.	V.S.	Total	Mean		

Temperature of the cold limb (t_1)=···°C

Steady ,, ,, hot ,, (t_2)=···°C

Mean coefficient of expansion

$$=\gamma_r=\frac{h_2'-h_1'}{\{h_1-(h_2'-h_1')\}\,(t_2-t_1)}=\cdots\text{per °C}$$

Precautions.

(i) The cathetometer must be carefully levelled. (The same applies to the travelling microscope when this is used.)

(ii) The steady condition must be reached.

(iii) Cross-tubes must be efficiently cooled.

(iv) There must be no parallax between the cross-wires and the image.

Under "Method followed" give a short description of what you have done. As the apparatus may not be the same in different laboratories, we leave the 'write-up' to the student.

Oral questions.

1. Distinguish between the real and apparent coefficients of expansion of a liquid. Which one you determine in this experiment ?

2. How is it that the expansion of the vessel does not affect your result ?

3. Will the result alter if (a) the lengths were measured in inches, (b) the temperatures were measured in °F ?

4, What are the common sources of error in the experiment ?

5. Why do you cool the cross-tube ?

6. Why do you measure the height of the mercury column from the axis of of the cross-tube ?

7. What is parallax ? Why is it necesary to avoid parallax between the cross-wires and the image ?

Answers.

1. The coefficient of (volume) expansion of a liquid treated *independently* to the expansion of the container is the *real* or *absolute* coeff. of expansion. Considered *relative* to the expansion of the container it is the *apparent* coefficient. The former.

2. Change of temperature changes the density of a liquid. This change is independent of the nature of the container. Hence density changes are related to the absolute coefficient of expansion.

3. An expansion coefficient independent of the unit in which the length, area or volume is measured. But it is proportional to the unit of temperature difference. Since 1°F=(5/9)°C, the result will be reduced by (5/9) if the fahrenheit scale was used,

4. The errors depend on the type of appratus used. In the one described here h_1 may not be equal to h_2. Also h_1' and h_2' are generally not at the same temperature. Since the temperature along each of the vertical tubes varies from place to place, assumption of a uniform temperature over one portion and another temperature over another portion are assumptions. Their non-fulfilment introduces an undeterminable error. Besides, heights should be measured from the lowest portion of the lower cross-tube.

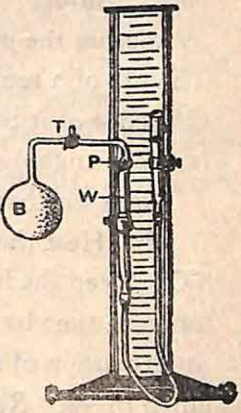
5. To minimize mixing of hot and cold mercury.

6. It provides a convenient refence position. If there are convection current it is easy to treat them assuming the warm current to be above the axis and the cold current below it.

7. Parallax is the difference in position between an image and a close-by object, or between two images which are sought to be formed at the same place. Since a height is equal to the difference in the two positions of the crorss-wire, it is necessary that the images of points between which the vertical distance is to be measured form images coincident with the cross wires.

4-5. To measure the coefficient of increase of pressure of air at constant volume

Description of appapatus. The apparatus consists of a bulb B (Fig 4.5) connected by means of a capillary tube to a wider glass tube W. H is another glass tube of relatively wide bore, open at both ends, and serves as a mercury reservoir. W and H are connected together by a thick-walled Indian-rubbe tube and may be raised or lowered along a vertical stand to which they can be clamped. By raising or lowering H, the level of mercury in W can always be brought up to a certin mark P near the junction of W and the capillary tube. The mark usually consists of a pointed index fixed inside W. A threeway tap enables the bulb to be filled with dry air. A large beaker or copper vessel containing water is so supported that B may be completely immersed in the water. A scale is fixed to the stand between W and H. From it the difference of level in W and H can be measured. The entire apparatus is supported on levelling screws, which are adjusted to make the scale vertical.



Fig, 4.5

Theory. When the temperature of a given mass of gas is increased, but its volume is kept constant, the pressure increases. For each degree celsius increase of temperature, the pressure increases by a constant fraction of the pressure at 0°C. This fraction is called the *pressure coefficient* (γ_v) of the gas at constant volume. If

$$P_0 = \text{pressure at } 0°\text{C},$$

$$P = \text{pressure at } t°\text{C},$$

then

$$P = P_0(1+\gamma_v t)$$

or

$$\gamma_v = \frac{P-P_0}{P_0 t} \tag{4-5.1}$$

List of apparatus. Constant volume air thermometer ; large water bath ; Bunsen burner ; tripod ; thermometer ; stirrer.

Instruction. (1) Surround the bulb B by a water bath at the room temperature. Immerse a thermometer in the bath. Stir the bath and allow the bulb to acquuire the temperature of the bath. Adjust the position of H so that the mercury surface in W touches the pin P. Read the levels of mercury in W and H. The use of a set-square may be helpful in taking these readings. One edge of it is placed parallel to the scale and the other edge (at right angles) set tangential to the mercury meniscus.

Note the bath temperature and the height of the barometer.

(2) Heat the bath slowly until the temperature rises by about 8°C. Keep the bath temperature constant near about that value for some time by manipulating the flame of the burner. Owing to expansion of air you will find that mercury has been forced down in W. Raise H and bring the mercury back to the index. Stir the bath well. Carefully adjust the mercury level in W so that it just touches P. Read the level in H. Note the bath temperature.

(3) Repeat the above observations at intervals of 8° to 10°C. Take at least six readings At each value of the bath temperature, hold the temperature constant for at least five minutes, preferably longer. Be careful to stir the bath well.

(4) At the end of the experiment lower the reservoir H a little below its initial position, as otherwise mercury may be drawn into B when the bulb cools.

(5) Preferably read the barometer again at the end of the experiment. Take the mean of the barometric heights.

Remember that the pressure of the gas in B at any temperature is equal to the barometric height plus the difference of mercury levels in W and H at that temperature.

(6) Calculate the pressure (P) corresponding to each bath temperature (t) and plot P against t on a graph paper. [In *plotting the graph* the value of the temperature at the origin of the co-ordinate system should be 0°C, as it is required to find the pressure corresponding to 0°C from the graph. The value of the pressure at the origin may be taken to be 68 cm of mercury or thereabouts, since the zero-point pressure is ordinarily likely to be above this value] Draw the best straight line through the points plotted [See Sec. 1-16, (vi)] and find P_0 from the graph by extrapolation.

The graph represents the relation between the pressure and temperature of the experimental gas at constant volume.

Take any convenient point on the graph, preferably corresponding to a large value of t, and substituting its co-oridnates in Eq. 4-5.1, find the value of γ_v.

Experimental results :

Barometer values.

vernier constant :

Smallest main scale division=···mm

···main scale div.=···vernier div.

∴ Vernier consant=···mm=···cm

Barometric height :

No. of obs	M. S. cm	V. S. cm	Total cm	Mean (h) cm
Initial				
Final				

Pressure—temperature record :

Obs.	Temperature of the bath (in °C)	Position of mercury level at index point (in cm) (a)	Position of mercury level in reservoir (in cm) (b)	Excess Pressure (h' cm of Hg) (b) – (a)	Total pressure ($P = h \pm h'$ cm of Hg)
1					
2					
etc.					

A P—t graph (last column against second column,) is drawn.

[*Note* : If the mercury level in H is lower than that in W, h' is negative.]

Result.

From the graph, pressure P_0 at 0°C= ···cm of mercury

and P at ···°C= ··· „

$$\therefore \quad \gamma_v = \frac{P - P_0}{P_0 t} = \cdots \text{ per °C.}$$

Method followed (1) The bulb was surrounded by a water bath. The mercury reservoir was adjusted so that the mercury touched the pin near the capillary at the room temperature. The bath temperature, the position of the mercury level in the two limbs and the barometric height were noted.

(2) The bath temperature was raised by steps of about 8°C, and held constant at each level for at least 5 minutes. The mercury reservoir was raised till the mercury in the other limb touched the index pin. The constant bath temperature and the positions of the mercury levels in the two limbs were noted for every value where the temperature was kept constant. A total number of ··· readings (at least six) was thus secured. The burner was put out.

(3) The mercury reservoir was lowered to a value a little lower than its initial level. The barometer was read again.

(4) The gas pressure P was calculated in centimetres of mercury for each constant temperature t. P was then plotted against t, and the value of P_0 corresponding to 0°C obtained from the graph. Taking some other point on the graph γ_v was calculated.

Precautions :

(i) The bath temperature was held constant for at least five minutes.

(ii) The bath was well stirred.

(iii) The scale was vertical.

(iv) In reading the mercury levels parallax was avoided.

(v) The mercury reservoir was lowered at the end of the experiment to avoid suction of mercury into the bulb.

N.B. (*a*) The value of γ_v so obtain is uncorrected for the expansion of the bulb. This correction is unnecessary for class-work.

(*b*) As students often find it difficult to maintain temperatures above 60°C constant, some teachers prefer rises of temperature by 5°C at a time instead of 8° to 10°C advocated in the text.

Oral questions.

1. Define the pressure-coefficient of a gas. Does it depend on the mass of the gas or its pressure ? On what factors does it depend ? Why do we insist on the volume remaining constant ?

2. Suppose mercury is replaced by water in this experiment. Will you object to it ? What are your grounds ?

3. Why should the air in the bulb be dry ?

4. Why do you use a narrow tube connecting B and W ?

5. Will there be any harm if the index were placed well down W ?

Answers.

1. The pressure coefficient (at constant volume) of a gas is defined as the constant fraction of the pressure at 0°C by which the pressure of a given mass of gas increases at constant volume for each degree celsius rise of temperature. (See Theory).

It does not depend on the mass of the gas. But it depends *slightly* on the initial pressure. As the initial pressure is reduced γ_v for all gases tends to the same value, 1/273 per°C. γ_v depends slightly on the nature of the gas and its initial pressure.

A change in volume alone will also change the pressure (Boyle's law). Here we want the effect of temperature alone on the pressure. Hence volume has to be kept constant.

2. There are two grounds for opposition in using water. (a) The water column has to be 13.6 times higher than the mercury column used for measuring

pressure. (b) Water in the tube will staturate the gas bulb. So the observed expansion will not be that of dry air.

3. Moist air has a pressure coefficient dependent on the amount of water vapour present per unit volume.

4. To keep the *dead space* between B and W as small as possible. The temperature of this portion is uncertain. It is not that of B.

5. It will increase the volume of the dead space, and introduce an error in the result which will be very difficult to estimate.

4-6. To measure the coefficient of volume expansion of air at constant pressure

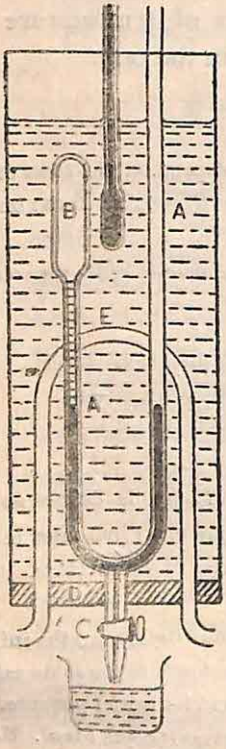


Fig. 4.6

Description of apparatus. It consists of a U-tube AA (Fig. 4.6), one end of which is open to the atmosphere, while the other end has a bulb B attached to it. The bulb and a part of the stem of A adjacent to B are graduated in cubic centimetres. At the middle of the U-tube is attached a short tube C fitted with a stop-cock. The U-tube is surrounded by a water bath which can be heated by steam passing through a copper tube E (or steam may be passed through an open glass tube dipped in the bath). The bulb B and part of A are filled with the experimental gas, which stands over concentrated sulphuric acid in A. The acid keeps the gas dry. A thermometer immersed in the bath reads the temperature. A stirrer is used to stir the water.

Theory. If the pressure of a given quantity of gas is kept constant and the temperature is allowed to change, the relation between the volume and the temperature can be expressed in the form,

$$V_t = V_0(1+\gamma_p t) \qquad (4\text{-}6.1)$$

where V_t is the volume of the gas at t°C, V_0 is the volume at 0°C and γ_p is a constant coefficient, called the *coefficient of expansion of volume at constant pressure* (or the volume coefficient).

$$\therefore \quad \gamma_p = \frac{V_t - V_0}{V_0 t} \qquad (4.6.2)$$

List of apparatus. Expansion apparatus (constant pressure air thermometer), boiler and accessories for steam heating, strong sulphuric acid in beaker, small funnel, thermometer.

Instructions. 1. If necessary, pour strong sulphuric acid in the open limb of AA until the acid stands at a slightly higher level than in the closed limb. Open the stop-cock C slightly and allow the acid to run out of the tube drop by drop (and collect in a beaker). In this way adjust the acid levels to the same height in both limbs.

2. Insert a thermometer in the bath surrounding the tube AB. Stir the bath well. Take the reading corresponding to the top of the acid level in the closed limb. This gives in cm^3 the volume of the gas in the bulb at the temperature of the bath. Read the thermometer.

3. Allow steam to pass through E and stir the bath well. As the temperature rises, the gas in B expands and pushes down the acid, which rises in the other limb. When the temperature has gone up by about 8°C, cut off the steam, stir well and equalise the acid level in the two limbs by running out some acid through C. After the steam has been cut off, the temperature is found to rise by a small amount, remain stationary for some time and then fall. Read the temperature and the volume when the former is stationary. Stirring should be vigorous. When reading the volume *the acid levels must be adjusted to equality*.

4. Pass the steam again and raise the temperature by a further 8°C or so. Repeat at this temperature the same adjustments and take readings as mentioned in the last paragraph. Take at least six such readings at different temperatures.

5. Plot the volume against temperature, and from the graph find V_0 by extrapolation. From the graph take a value of the

volume (V_t) corresponding to a high value of t and substitute V_o, V_t and t in Eq. 4-6.2 to get γ_p.

6. Note the atmospheric pressure before and after the experiment. A change in it will produce a change of volume even if the temperature is constant.

Experimental results :

Atmospheric pressure : Enter as in 4-5.

Volume-temperature record :

Obs.	1	2	3	4	5	6
Temp. (in °C)						
Vol. (in cm³)						

(Draw the graph of volume against temperature)

From the graph, the volume (V_o) at 0°C= ··· cm³

volume (V_t) at ···°C (t)= ··· cm³.

$$\therefore \quad \gamma_p = \frac{V_t - V_o}{V_o t} = \cdots \text{ per °C.}$$

Precaution. It is necessary to keep the temperature constant for several minutes in order that temperature equilibrium may occur between the gas and its bath.

Oral questions.

1. Why do you use sulphuric acid in the tube ? Will it do if mercury was used ? If water was used ?

2. Should the two limbs of the tube be of the same diameter ? What would be the harm if the open limb had a very small diameter ?

3. Do you consider it necessary to note the barometric pressure before and after the experiment ? Why ?

4. On what factors does the volume of the gas depend ?

5. What is Charles' law for gases ?

6. Distinguish between the volume-coefficient and pressure-coefficient of a gas.

Answers.

1. It is necessary to keep the gas dry. Expansion of water vapour is larger than that of air.

2. If the bores are rather narrow, say of 2mm or less in diameter, they should have the same diameter. If the bores are large they need not be the same in diameter. Unequal bores will not matter until capillary effect makes its presence felt. A narrow bore shows capillary effect depending on its diameter.

3. Yes, it is necessary. The volume of a constant mass of gas depends on the pressure even if the temperature is constant (Boyle's law).

4. Volume of a given mass of gas depends both on its pressure and temperature.

5. At constant pressure, the volume of a given mass of gas is proportional to its absolute temperature. (Or, use any equivalent form.)

6. The *volume coefficient* (γ_p) of a gas is the fraction of the volume at 0°C by which the volume increases per °C rise in temperature, the *pressure remaining constant.*

The *pressure coefficient* (γ_v) of a gas is the fraction of the pressure at 0°C by which the pressure increases per °C rise in temperature, the *volume remaining constant*. (The subscript, p or v, shows which parameter remains constant.)

4-7. To determine the thermal conductivity of a metal using Searle's apparatus

Description of apparatus. Searle's apparatus (Fig. 4.7) for the determination of the thermal conductivity of a metal,

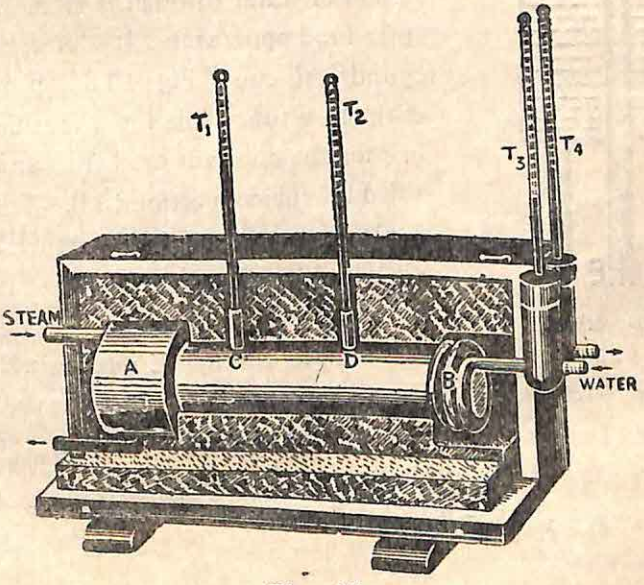


Fig. 4.7

such as copper, consists of a thick, polished bar of the metal, about 5 cm in diameter, and 20 cm in length, surrounded by dry felt and enclosed in a wooden box. It is fitted at one end into a cylindrical chamber A through which steam can be passed. Near the other end a spiral B of thin copper tubing is fixed on the bar. A stream of cold water may be passed through the tubing The temperature of the water as it enters and leaves the tube is indicated by the thermometers T_3 and T_4.

Holes are drilled in the bar at C and D, a known distance apart, and thermometers T_1 and T_2 are placed in tubes fixed in these holes. The holes should contain mercury to ensure good thermal contact.

Steam passing through A maintains one end of the bar at 100°C. Appreciable loss of heat from the curved sides of the bar is prevented by the felt packing as well as the polish of the surface which reduces radiation loss. The water circulating through B maintains that end of the bar at a lower temperature. This temperature is kept steady by sending a steady stream of water through B from a constant-head apparatus. It consists of a cylindrical can (Fig 4.8), provided with three tubes, one for the inlet (I) one for the constant-head (E), and the third (F) for connection to B. The can is placed at a convenient height throughout the experiment. The inflow is faster than the outflow. The excess water flows through E into a sink.

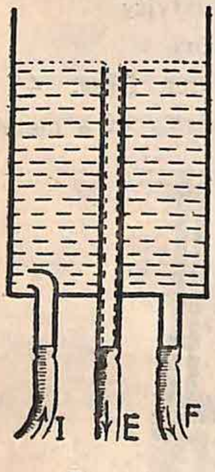


Fig. 4.8

Theory. Let a steady temperature gradient be maintained along a bar of cross-section A. Then the heat Q flowing through any cross-section of the bar in time t is given by

$$Q=KA\frac{\theta_1-\theta_2}{d}t \quad \dots \quad (4\text{-}7.1)$$

where K=thermal conductivity of the material of the bar, and θ_1 and θ_2=temperatures at two places on the bar separated by a distance d.

If this heat raises the temperature of m g of water from θ_3 to θ_4, then

$$Q=m(\theta_4-\theta_3).$$

$$\therefore \quad K=\frac{d}{A}\cdot\frac{\theta_4-\theta_3}{\theta_1-\theta_2}\cdot\frac{m}{t}. \quad \ldots \quad (4\text{-}7.2)$$

List of apparatus. Searle's conductivity apparatus, four thermometers, steam passing requisites, water flow requisiter, a pair of dividers and a diagonal scale, slide callipers, graduated cylinder, stop watch.

Instructions. Place the boiler, about three-fourths full of water, on the burner for the water to boil but do not connect to the steam inlet of the apparatus at this stage. While steam is being formed carry out the following :

1. Open the box and measure the diameter of the rod with a pair of slide callipers at several places.

2. Measure the distance d between the centres of the holes (C and D) by means of a pair of dividers and a diagonal scale. Take several readings.

3. Insert the four thermometers in position. If necessary, put mercury in the holes C and D. Close the box. Connect the steam inlet to the boiler. Lead the exhaust steam into a suitable vessel containing a little water.

4. Connect the constant water-head apparatus correctly to the water-tap and the inlet end of the copper tubing. Allow the overflow water from the can to run into a sink. At this stage the outgoing water from the cold end of the main apparatus may be led into the sink.

Use a pinch-cock on the rubber tube connecting the can and the apparatus. Close this pinch-cock and open the water-tap. When you find the overflow from the can running into the sink, open the pinch-cock and adjust it until the outflow from this tube is about 5 cm^3 per second. [This may be observed by means of a graduated cylinder and a stop-watch. Such a preliminary adjustment of the rate of flow is helpful but not essential. See that there is no leakage of water at the corks through which the thermometers T_3 and T_4 pass.

5. Note down the temperatures of all the thermometers at intervals of 3 to 5 minutes until you find that they are steady (for about 10 minutes). The difference between θ_4 and θ_3 should be about 10°C. If it is too small or too large, the rate of flow of water should be altered accordingly.

Any alteration in the rate of flow affects the readings of T_1, T_2 and T_4. Hence, the time-temperature record has to be continued until the steady condition is again established.

6. After you have reached a satisfactory steady condition, collect about 500 cm^3 of outflow water from the apparatus and note the time required for the collection. The mass of this water may be found by weighing, but you may, without loss of accuracy, measure its volume with a graduated cylinder and take 1 cm^3 to weigh 1 g.

7. If time permits, the rate of flow of water may be slightly altered, so that $\theta_4 - \theta_3$ still lies between 10° and 15°C and another collection made. The two sets of data should be used independently for determining K.

Experimental results :

Constants of the callipers :

Smallest scale div.=···mm

···scale div.=···Vernier div.

∴ Vernier constant=$1\ s - 1\ v$=···mm=···cm.

Zero error=···cm (to be added/subtracted)

Correct readings for the diameter of the bar (in cm) :

No. of obs.	Main scale reading in cm	Vernier reading	Value of vernier reading in cm	Diameter in cm	Mean diameter in cm	Corrceted diameter D in cm
1 (a)						
(b)						
2 (a)						
(b)						
etc.						

Distance between centres of the holes (measured, with dividers and diagonal scale) :

(i)	(ii)	(iii)	Mean
…	…	…	…cm (d)

Thermometer readings (in °C) :

Time (in minutes)	θ_1	θ_2	θ_3	θ_4
0	…	…	…	…
3	…	…	…	…
6	…	…	…	…
9	…	…	…	…
12	…	…	…	…

(Continue the record until all readings remain constant for three successive intervals.)

Mass of water collected in…s (t)=…g (m).

Area of cross-section of the rod$=\pi(D/2)^2$

$$K=\frac{d}{\pi(D/2)^2}\cdot\frac{\theta_4-\theta_3}{\theta_1-\theta_2}\cdot\frac{m}{t}$$

=…calorie per sec. per cm per °C. (cal s^{-1} cm^{-1} $°C^{-1}$).

Method followed (brief statement) :

Water in the boiler was first put to boil. The following steps were then taken.

1. The diameter of the metal rod under investigation was measured.

2. The distance between the centres of the two holes in the rod was measured.

3. The steam chamber was connected to the boiler. The water supply was connected through the constant-head apparatus to the inlet end, and thermometers inserted.

4. The temperatures of all the four thermometers were noted at intervals of…minutes until they were found to be steady. These steady values were used for calculation.

5. In the steady state, the time for collection of···cm^3 of water was noted.

6. From the data so obtained the result was calculated.

Oral questions

1. Define the thermal conductivity. What is its unit in the c.g.s. system ?

2. Why is it considered necessary to insulate the bar thermally and to polish its surface ?

3. Is the method applicable without modification to bad conductors ? Why ?

4. What is the temperature gradient in your experiment ?

5. In deriving the formula what has been assumed regarding the direction of flow of heat ?

Answers.

1. Thermal conductivity of a material is the amount of heat flowing across unit area per unit time when the temperature gradient is unity. The unit in the cgs system is calories per centimetre per °C per second.

2. In Searle's experiment, all the heat should pass from one end of the bar to the other. No part of it should be lost by radiation and conduction through the sides.

Radiation and conduction are minimized by polishing the bar and covering it by non-conducting material.

3. The method cannot be applied, without modification, to bad conductors, as very little heat would pass axially through a thick cylinder of poorly conducting material. The thickness of the cylinder must be reduced.

4. The temperature gradient is $(\theta_1 - \theta_2)/d$.

5. In deriving the formula, it has been assumed that the lines of heat flow are perpendicular to the cross-section of the tube. In other words, the heat flow is axial (that is, parallel to the axis of the cylinder).

CHAPTER 5

SOUND

5-1. Sonometer (Monochord). The sonometer required for our purpose is a monochord as shown in Fig. 5.1. It consists of a hollow rectangular wooden box with a steel wire stretched above it. One end of this wire is fixed to a pin and the other passes over a pulley attached to the box and carries a scale pan. Weights are placed on the pan to provide adequate tension to the wire. The vibrating length of the wire can be adjusted by means of two wooden bridges with sharp metallic edge over which the wire passes. A metre scale is fixed parallel to the wire. The bridges can slide along the scale and thus alter the length of the wire between them.

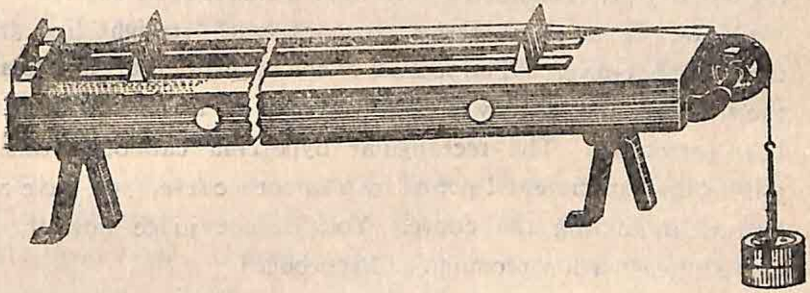


Fig. 5.1

When the wire vibrates, its vibration is communicated through the bridges to the board on which they rest. The board, so thrown into forced vibration, forces the air inside the hollow of the box to vibrate. These vibrations are communicated to the external air through the openings in the sides of the sonometer. The intensity of the sound directly derived from the string or the board is feeble.

3-2. To draw the n—l curve and hence to find the frequency of a tuning fork

Theory. *For a given tension*, the frequency (n) of a fork is inversely proportional to the length l of the sonometer wire which is in unison with the fork.

$n \propto 1/l$, provided the sonometer wire remains at the same tension.

So if a graph is drawn with the frequencies of known tuning forks along the X-axis and the corresponding lengths for resonance along Y-axis, the curve will be a *rectangular hyperbola.* A graph of $1/l$ against n will be a *straight line.* The unknown frequency n' of any fork may then be determined from the graph by finding the length of the sonometer wire with which it is in unison.

Note. It is much easier to work with straight line graphs than with curves. The scatter of the experimental points about the straight line clearly shows you how well the experiment has been performed. The rectangular hyperbola cannot do this. In joining the experimental points by a smooth curve, you have much latitude in guiding the curve. You cannot judge how the final curve agrees with a rectangular hyperbola.)

List of apparatus. Sonometer, hanger with requisite number of slotted $\frac{1}{2}$ kg or 1 kg weights, a set of five forks of known frequency (forks of frequencies 256, 320, 384, 426, 512 Hz form a standard set), a fork of unknown frequency (within the range of given frequenceis), striking rubber pad.

Instructions. Take a set of tuning forks of known frequencies covering the range in which the frequency of the unknown tuning fork may lie. Commence work with the fork of the *lowest frequency.*

1. Place a weight of, say, one or two kilograms on the hanger of the sonometer and move the bridges almost to the opposite ends. Pluck the wire and also strike the tuning fork against the rubber pad to set them into vibration. Compare the sounds emitted by them and satisfy yourself that the pitch of the tuning fork is higher than that of the wire.

Slide the vibrating fork along the wire starting from one bridge towards the other, lightly touching the wire all along with the central region of one of vibrating prongs. During this process you will hear a sharp cracking sound when the fork reaches a particular point of the wire. Move the bridge from which you started to this position. The length between the bridges now approximately equals the length for unison. If necessary, reduce the load on the pan so that this length is relatively large.

Then place the vibrating fork with its shank on the wooden board near one of the bridges and slowly alter the distance between the bridges until the string vibrates with maximum amplitude. To facilitate your work, place a rider (a very light piece of folded paper of the shape of ∧.) on the wire in its middle. When the tuning fork and the wire are in unison, the vibrating fork will set the wire into vibration and the rider will be thrown off.

If you now set both the tuning fork and the wire simultaneously into vibration and listen to the sound from both, you will probably hear *beats*. It may require a little training of the ear to recognise them. Slowly alter the vibrating length until the beats disappear. You then have unison.

2. Now measure the length of the wire between the bridges. Make three independent adjustments and take the mean.

3. Keeping the same tension, repeat your observations with the other forks of known and unknown frequencies and find the corresponding lengths for resonance.

4. Plot points on a squared paper with the frequency as abscissa and the corresponding length for resonance as ordinate and draw the graph. If the points do not lie on a smooth curve, draw the best curve through the points such that the sum of the vertical distances of the points above the curve equals that below it. From the graph find the frequency of the unknown fork. (Also draw a curve of $1/l$ against n and use this too to find the unknown frequency.)

Experimental results :

Weight on the scale pan=···kg.

No. of Obs.	Frequency of the fork (n)	l (in cm)	Mean l (in cm)
1		(*i*) (*ii*) (*iii*)	
2 (etc.)		(*i*) (*ii*) (*iii*)	

Draw a graph of the fourth column against the second. From the graph the frequency of the given tuning fork=···per sec.

Note. 1. The reciprocal of l plotted against n will give us a straight line. It will be easier to draw this graph, which passes through the origin, and hence to find n'. In the reciprocal do not keep more than three significant digits. Known values of n have as many (3 significant digits).

2. Unless you reach a state of near unison *by hearing* and try the rider method from the beginning, you may get a pseudo-resonance at half the proper length. This will completely vitiate your work. *Be careful about it.*

Method followed (a brief statement) :

1. With the fork of lowest frequency and a load of ··· kg for tension, I found by trial, an approximate length for resonance. Resonance was perfected by removal of beats on finer adjustment. This was repeated thrice. The mean length of wire for resonance was noted, together with the frequency of the fork.

2. With the tension unchanged, the operation was repeated for all the other forks, including the unknown one.

3. A curve was drawn of l against n, the frequency. The value of n obtained from this graph corresponding to the value of l for the fork of unknown frequency, gives the unknown frequency of the fork.

4. Another graph was drawn, plotting $1/l$ against n. This was a straight line passing through the origin. The unknown

n value was determined from this graph also. This value is more reliable.

[**Note.** In drawing the straight line graph (n vs. $1/l$) *we have the* origin (0, 0) as one point. The best experimental point is $\overline{(1/l)}, \bar{n}$ (mean values). These two points define the best straight line the data can give. See Sec. 1-16(a).]

Oral questions

1. Can you give examples of both forced vibration and resonance from your experiment ?

2. What part does the sonometer box play ?

3. State the laws of vibration of a stretched string.

4. What do you understand by the fundamental and overtones of a note ? What kind of overtones does a stretched string produce ?

5. Will there be resonance if you double or halve the length between the bridges, while other factors remain unaltered ?

6. How dees the turning fork communicate its vibrations to the board when you press the shank on the latter ?

Answers.

1. When the vibrating fork is pressed on the sonometer board, it throws the board, the string and the air inside the box into forced vibration. On proper adjustment resonance occurs between the fork and the wire only.

2. A vibrating string or fork is poor radiator of sound energy. The sonometer box increeses the strength of this sound by forced vibration.

3. (Remember the formula $n=(1/2l)\sqrt{T/m}$, and state the laws with its help.)

4. A 'note' is a musical sound, generally consisting of several vibrations of different frequencies. The vibration of the lowest frequency is called the 'fundamental'. The rest are called 'overtones'. The overtones of a stretched string have frequencies which are *integral multiples* of the fundamental frequency.

5. There will be a kind of resonance we sometimes call *pseudo-resonance*, that is, false resonance. The amplitude of vibration increases but not to the same extent as at true resonance,

When the length is half that at true resonance, the fork supplies energy to the string in every alternate vibration. For double length, it is supplied in each half vibration.

6. As the fork vibrates, both its prongs simultaneously move outward or inward. The bend to which the stem (or shank) is attached moves up and down

with the frequency of the fork. When the stem is pressed on the board, it exerts a periodic downward thrust on the board with the frequency of the fork.

5-3. To determine the frequency of a fork with a sonometer.

Theory. Let the fork produce resonance with a length l of the sonometer wire under tension T and having a mass m per unit length. The frequency n of the fork is related to these quantities by the formula

$$n=\frac{1}{2l}\sqrt{\frac{T}{m}} \qquad (5\text{-}3\,1)$$

List of apparatus. Sonometer, hanger with a set of slotted $\frac{1}{2}$ kg or 1 kg weights, the fork under investigation, a striking rubber pad, a sample of wire the same as the sonometer wire, metre scale, accurate balance, weight box.

Instruction. 1. Ascertain the weight of the hanger. Place a trial load of 1-2 kg on the hanger. Remove the bridges almost to the ends of the scale.

2. Pluck the wire and strike the fork alternately to make sure that the *wire has a lower pitch than the fork*. If necessary, reduce the load on the hanger.

3. Having made sure that the wire has a lower frequency (pitch) than that of the fork, gradually reduce the vibrating length of the wire until the wire and fork appear to have nearly the same pitch. (Some students may not be good judges of pitch. They can use a very light Λ-shaped rider on the wire. At close resonance it will be thrown off.)

4. *Beats* may be heard in this condition. By finer adjustment of the bridges the beats should be reduced to zero. The wire and the fork are now in resonance.

5. Measure the length of the wire between the bridges (either from the sonometer scale or with a seperate metre scale, whichever is convenient). Disturb either of the bridges and reset to perfect resonance. Measure the length. Get altogether three readings in this way.

6. Now *increase* the load on the hanger by, say, $\frac{1}{2}$ kg. Resonance will now take place at some *greater length* of the wire. Find three exact resonating lengths in the same way before.

7. Operation 6 may be repeated with a further increase in load, if time permits. Do not use too short lengths. The relative error will be higher.

8. Take the sample wire, measure its length, and find its weigh carefully to the nearest milligram. It is necessary to have 3 significant digits in the value of m, and as many in l and T.

Tabulate data as follows:

Experimental results:

Weight of hanger = ···kgf (W')

Obs.	Load (W) on hanger (kgf)	Resonant length (l cm)	Mean l in cm	*Tension* $T = (W+W')$ kgf
1		(*i*) (*ii*) (*iii*)	...	...
2 (etc)		(*i*) (*ii*) (*iii*)	...	...

Mass per unit length of the sample wire (m):

Length (L) of the sample wire in cm	Mean L in cm	Mass (M) of the Sample wire g	Mass per unit length $m = M/L$ g/cm
(i) (ii) (iii)		$(\cdots+\cdots+\cdots)$ g $+(\cdots+\cdots+\cdots)$mg $=\cdots$g	

Calculation:

Obs.	l (cm)	$T = (W+W') \times 9.8 \times 10^5$ dyn	m g/cm	$n = (1/2l)(T/m)^{\frac{1}{2}}$ Hz
1				
2				
etc.				

Result: Mean value of $n = \cdots$Hz.

Method followed (a brief statement) :

1. With a load of ··· kg on the hanger, I found by trial an approximate length for resonance. Resonance was perfected by total disappearance of beats. Three independent settings were made for the same load, and the mean value was used.

2. Operation 1 was repeated for other loads.

3. Mass per unit length of the sonometer wire was determined from the sample wire provided.

4. The result was calculated in the way shown.

[For 'Oral questions' and 'answers' see those under Sections 5-2 and 5-4.]

5-4. To determine the density of the material of a wire with a sonometer

Theory : When a tuning fork of frequency n is in unison with the fundamental of a string of length l the frequency of the fork is given by

$$n=\frac{1}{2l}\sqrt{T/m},$$

where T is the tension of the string measured in *dynes* and m is its mass per unit length.

$$\therefore \quad m=\frac{T}{4l^2n^2}.$$

If ρ is the density of the material of the wire and r its radius, then

$$m=\pi r^2\rho$$

or $$\rho=\frac{m}{\pi r^2}=\frac{T}{4\pi r^2l^2n^2} \qquad (5\text{-}4.1)$$

Knowing n and determining T, r and l, ρ may be computed.

List of apparatus. Sonometer, hanger with requisite weights, a fork of known frequency n, striking pad, metre scale, screw gauge.

Instructions. Measure the radius of the wire by means of a screw gauge in the usual way.

Determine the lengths for resonance with different tensions as in the last experiment and find the mean value T/l^2.

Record your data as follows and calculate ρ from Eq. 5-4.1.

Experimental results :

Constants of the screw gauge **:**

···full turns = ···mm.

Pitch (p) = ··· mm.

Total circ. div. s (n) = ···

Least count (p/n) = ··· mm.

Zero error = ···mm (to be added / subtracted)

Diameter (d) *of the wire (in mm)* **:**

[(a) and (b) are at right angles]

No. of obs	Linear sc. reading (cm)	cir. sc. reading	value of cir. sc. reading (cm)	Diameter of the wire (cm)	Mean diameter (d) (cm)
1. (a) (b) etc.					

$\therefore$ Corrected d = ···mm ± ···(zero error)

= ··· mm = ···cm.

$\therefore$ $r = d/2$ = ··· cm.

Frequency of the given tuning fork n = ···Hz.

Weight of the hanger = ···kgf.

No. of Obs.	Tension (T)-in kgf	l (in cm)	Mean l	T/l^2	Mean T/l^2
1		((ii) (iii)			
2		(i) (ii) (iii)			
3		(i) (ii) (iii)			

Since T' is in kgf, we have to convert it into *dynes* by multiplying it by 1000. $1000 \times 980 = 9{\cdot}8 \times 10^5$ (g taken as 980 cm/s^2).

Remember that T' in kgf = weight of the hanger in kg + the kg loads on the hanger.

$$\therefore \quad \rho = \frac{9{\cdot}8 \times 10^5 T'}{4\pi r^2 l^2 n^2} = \cdots \text{ g/cm}^3.$$

[For 'write-up' and 'oral questions', see the last experiment.]

5·5. To determine the frequency of a tuning fork by Melde's experiment

Description of apparatus. The apparatus used for this experiment is as shown in Fig. 5.2. A string attached to one of the prongs of a rigidly mounted tuning fork, passes round a pulley and carries a scale pan at the other end. Weights are placed on the scale pan to stretch the string and keep it in tension. Two pin-pointers carried on two movable stands are used for marking the positions of the nodes on the string.

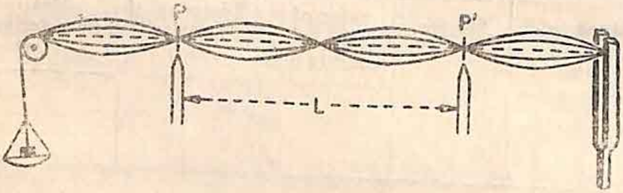


Fig. 5.2 (L = Wavelength of the stationary waves formed. P, P' = nodes.)

Theory. When the fork is excited, transverse vibrations are propagated along the string with a velocity

$$v = \sqrt{\frac{T}{m}}$$

Where T = tension of the string and

m = mass of the string per centimetre.

The frequency of vibration is equal to that (n) of the fork when the *plane of vibration of the fork is perpendicular to the string*

(*Transverse arrangement**). The wavelength λ is, therefore, $v/n\ (=L)$.

If, for a given tension, the length of the string is properly adjusted so as to make its total length equal to an integral multiple of $\lambda/2$, a stationary wave pattern will be formed. Let l be the length of a loop, *i.e.*, the distance between successive nodes. Then, in the *transverse mode*, that is when the fork vibrates perpendicular to the string,

$$l=\lambda/2=\tfrac{1}{2}v/n=\frac{1}{2n}\sqrt{\frac{T}{m}}$$

or

$$n=\frac{1}{2l}\sqrt{\frac{T}{m}} \tag{5-5.1}$$

If M is mass of the scale pan together with that of the loads placed on it and the hanging part of the string, then

$$T=Mg \tag{5-5.2}$$

where g is the acceleration due to gravity.

Combining Eq. 5-5.2 with 5-5.1 we can find out n when l, m and M are known.

List of apparatus. A length of string (soft but strong), metre scale, delicate balance, weight box, mounted fork of low frequency (say. 64-80 Hz), pulley on stand with adjustable height, pan with suspension thread, small known weights, two vertically mounted pins (preferably on heavy base, and sharp ends pointing upward).

Instructions : 1. Take a good length of the thread supplid for your experiment and weigh it correct to a milligram. Measure its length and calculate the mass per unit length of the given thread.

2. Set up your apparatus as shown in the figure. The fork must vibrate perpendicular to the length of the string ; this is the *transverse arrangement.*

---

*But if the fork vibrates parallel to the length of the string (*longitudinal arrangement*), the frequency of vibration of the string is half that of the fork. Hence the wavelength on the string is $2v/n$

3. Place a 10 or 15 g weight on the scale pan and begin your experiment with about a metre length of the thread in between the pulley and the tuning fork. Excite the tuning fork by drawing a resined bow sharply at one of the edges of the prongs and adjust the length of the thread until the vibrating loops come out very clearly. Set up two vertical pin-pointers by means of clamps and mark out the extreme nodes. Count the number of loops in between and measure accurately the distance between the pointers by means of metre scale.

4. Repeat your observations a number of times by independently adjusting the length of the thread as well as the position of the pointers. Find mean l for the given tension.

5. Note also the length of the vertical portion of the thread which carries the scale pan including the knot which fastens the scale pan.

6. Repeat your experiment for two other loads on the scale pan. Weigh the scale pan by means of a balance correct to 10 milligrams.

Experimental result :

Length of the thread taken for weighing=…cm.

Mass of the thread=…+…+…+…=…g.

∴ Mass per unit length of the thread (m)=…g/cm.

Mass of the scale pan (P)=…+…+…+…=…g.

Weight on the scale pan (Q)=…g.

No. of Obs.	Distance between the pointers	Number of loops between the pointers	l	Mean l
1	…cm	…	…cm	…cm
2	… ,,	…	…,,	
3	… ,,	…	…,,	

Length (L') of the vertical portion of the thread carrying the scale pan=…cm.

∴ Total tension $T=(P+Q+L'm)\ g$=…dynes.

Result :

$$n=\frac{1}{2l}\sqrt{\frac{T}{m}}=\cdots\text{Hz.}$$

[If time permits, repeat with some other value of Q, the weight on the scale pan.]

Note. The number of significant digits in the result is determined by that in m or T. This is generally two.

Method followed (a brief statement) :

1. The mass per unit length of the string was accurately measured.

2. Stationary vibrations were set up in a stretched string with the experimental fork vibrating in the transverse mode.

3. By fine adjustment the nodes on the string were made as clear as possible. This was done several times independently and the mean value of l noted.

4. T was determined from the weight of the scale pan with the load on it and the weight of the suspension string.

These provided sufficient data to calculate n, the frequency of the fork.

Oral questions.

1. What is meant by the 'fundamental frequency' of a stretched string ? On what factors does it depend ?

2. What are the modes is which a string can vibrate ?

3. What is a stationary wave ? How does it differ from a progressive wave ? How are stationary waves formed in this case ?

4. What are nodes and antinodes ?

5. Will there be any change in length between the nodes if the load on the pan is increased ?

6. On what factors does the velocity of transverse waves in a string depend ?

Answers.

1. The fundamental frequency of a stretched string is the frequency of the note it emits when vibrating in a single segment. The frequency is directly proportional to the square root of the tension and inversely to its length (for a given string).

2. The vibrations are transverse. The string may vibrate in one, two or any integral number of segments.

3. A stationary wave is the pattern of vibration in space and time in a limited portion of a medium in which two identical waves moving in opposite directions are superposed.

A stationary wave is confined to a limited portion of a medium. Bounded media exhibit stationary wave patterns. Unbounded media exhibit progressive waves. So long as a wave moves through a medium without meeting any obstruction or discontinuity, it is a progressive wave.

As the fork vibrates, progressive waves move out along the string. These are reflected from the other end (where the pulley is). The two wave systems moving in opposite directions, form stationary waves. The wave pattern so formed will be steady when the length of the string is integral multiple of half-wave lengths of the initial wave.

4. In a stationary wave pattern nodes are places of no (or minimum) particle displacement. Antinodes are places of maximum displacement.

5. Yes. n remaining constant l or λ ($\lambda=2l$) will increase if T is increased.

6. $v=T/m$. Velocity depends on tension and mass per unit length.

CHAPTER 6
LIGHT

6-1. Preliminary observations.

(i) **Parallax and how to avoid it.** In all cases of optical measurements where an accurate determination of the position of an image is sought, we take recourse to the *method of parallax.*

In Fig. 6.1, let P_1 represent a line drawn on a transparent screen and P_2, the image of a linear object. Both P_1 and P_2 stand perpendicular to the plane of the paper. An eye placed in the position E behind the screen sees both the lines coincident. As the observer moves his eye to the position E_1 or E_2, a relative motion occurs between P_1 and P_2. The same relative motion takes place even when the image is formed between P_1 and the eye. This relative motion ceases only when P_1 and P_2 coincide. This method of finding the position of an image by making it coincide with a reference line or point, is known as the *method of parallax.*

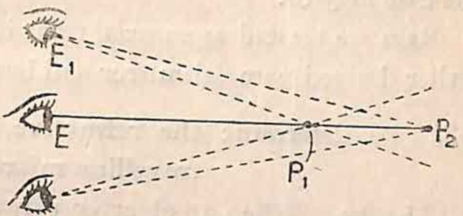


Fig. 6.1

In order to ascertain, during adjustment, whether the image is formed in front of or behind the screen, move your eye across the line joining P_1 and P_2. *If the image moves in the same direction as the eye* (with respect to P_1, the reference line), *then the image is farther away from the eye than the screen. If the image moves in the opposite direction, then it is nearer to the eye than the screen.*

A pin may be used for P_1. It will be called a **search pin.**

To avoid parallax, either the screen or the lens or mirror forming the image or the object itself is slowly displaced until there is no parallax between the image and the reference line.

(*ii*) **Sign convention.** In measuring object distance, image distance and focal length, we shall follow the convention of signs known as **Real is positive**. According to it, distances of real objects and real images are taken with a positive (+) sign. Focal lengths of concave mirrors and convex lenses are positive. Concave lenses have negative focal lengths. The distances are measured from the pole of a mirror or the optical centre of a *thin* lens, as the case may be.

Rays are treated as *paraxial* (that is, very close to the axis). The earlier derived paraxial mirror and lens formulae are applicable.

6-2. To determine the refractive index of a liquid with a travelling microscope

Theory. When an observer views vertically from air a point object inside a liquid, the object appears to him to be raised by a definite amount depending on its depth below the surface and the refractive index of the liquid relative to air. A narrrow, normal pencil of rays starting from P (Fig. 6.2), the point object. appears to come from a point P', which is the image of P. The refractive index of the liquid relative to the upper medium ('air' in the general case) is given by

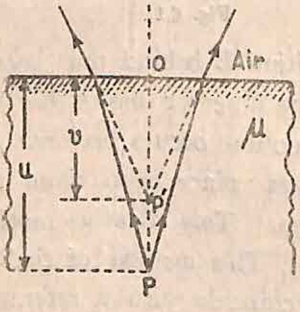


Fig 6.2

$$\mu=\frac{OP}{OP'}=\frac{u}{v}$$

when $OP=u$ is the real depth of P below the surface and

$OP'=v$ is its apparent depth.

List of apparatus. Travelling microscope, spirit-level, reading lens, experimental liquid, small flat-bottomed glass vessel to hold the liquid.

Instructions. 1. Place the travelling microscope (Sec. 2-5) on a table where there is sufficient light. By means of a spirit level adjust the stage of the microscope to be horizontal. Place the spirit level parallel to the line joining the levelling screws at the ends of the stage and turn the screws in opposite directions until the bubble reaches the centre. Now place the spirit level perpendicular to its former position and adjust the third levelling screw to bring the bubble at the centre.

Focus the eyepiece on the cross-wires or the micrometer scale with which the microscope is provided. Rotate the microscope about the horizontal axis, until its axis is vertical, *i e*, normal to the stage. This may be ensured by the coincidence of two marks on two discs facing each other, one carried by the microscope and the other fixed to the body of the instrument.

2. Find the vernier constant of the vertical scale by the usual method.

3. Raise the microscope up and place a small empty bowl or beaker on the stage with a surface scratch (*P* ; Fig. 6.3) on the inner surface of its bottom.

Focus the scratch till there is no parallax between it and the cross-wires. Take readings of the vernier on the vertical scale three times for three independent setting of the microscope.

4. Raise the microscope, and without disturbing the position of the beaker, pour a quantity of the given liquid into it. Focus the scratch as before three times and take readings.

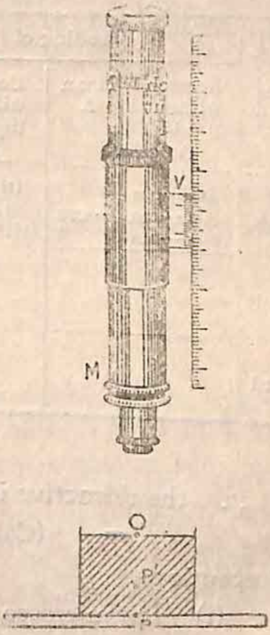


Fig. 6.3

(P' is the image of P as seen through the liquid.)

5. Raise the microscope further and dust a small quantity of lycopodium powder or cork dust (if lycopodium is soluble in the liquid) on the surface of the liquid taking care that the powder does not gather into heaps.

Focus the microscope on the dust so sprinkled three times as before and take readings.

6. Throw out the liquid from the beaker and clean it. Repeat the whole experiment at least for two other thicknesses of the given liquid.

Tabulate your data as follows.

Experimental results :

Value of the smallest division of the vertical scale

=······mm

······vernier divisions=······scale divisions

∴ Vernier const.=1 sc. div—1 vern. div.

=···mm······cm.

Liquid thickness	Reading of the microscope for the						Real depth $u=$ C—A	Apparent depth $v=$ C—B	$\mu=\frac{u}{v}$
	Scratch without liquid (A)	Mean A	Scratch with liquid (B)	Mean B	Surface of liqnid (C)	Mean C			
1st	(*i*) ···cm (*ii*) ···cm (*iii*) ···cm	···cm	(*i*) ···cm (*ii*) ···cm (*iii*) ···cm	···cm	(*i*) ···cm (*ii*) ···cm (*iii*) ···cm	···cm	···cm	···cm	
2nd									
3rd									

Mean $\mu=$······

∴ the refractive index of the given liquid relative to air =······(Calculate up to 3 decimal places.)

Precautions.

(*i*) The microscope axis should be vertical.

(*ii*) There should be no parallax between the cross-wires and the image.

(*iii*) To focus the microscope on P′ and O (Fig. 6.3), raise it by turning the screw S_2 (Fig. 2.7) at the top, which displaces the vertical vernier V_2 as well. Don't use the screw C for this purpose.

Note that S_2 displaces the microscope and the vernier, while C displaces the microscope only.

Method followed (A brief statement):

1. The vernier constant of the vertical scale of the microscope was determined.

2. The stage of the microscope was levelled and the microscope tube made vertical.

3. The eyepiece was focussed on the cross wires. The microscope was focussed on the surface mark at the bottom of the empty vessel. Three independent settings were made and the mean value used.

4. A thickness of about 2 cm of the experimental liquid was poured into the vessel. The microscope was raised to focus on the mark at the bottom. Readings were taken for three independent settings on the mark, and the mean value used.

5. A small quantity of fine cork dust was sprinkled on the top of the liquid. The microscope was further raised and focussed on thin dust. As before three readings were taken and the mean used.

From the data so secured, μ was calculated.

Note. Refractive index depends on the colour of light. Since white light has been used for the experiment, it is necessary to enquire for what colour (or wavelength) the value of μ found above holds good. The position of P' is different for different colours, The human eye being most sensitive to yellow-green light (wavelength about 5550 Å), the eye focusses the yellow-green image. Hence the value found is for yellow-green-light.

Oral questions.

1. What do you mean by refractive index ? On what factors does it depend ? When working in daylight, for what colour do you determine the refractive index ?

2. What is the necessity of taking a surface scratch and using finely divided powder ? What is the harm if a deep scratch or coarse powder is used ?

3, Does the accuracy depend on the thickness of the liquid ? Why ?

4. Is the method applicable to a volatile liquid ? Why ?

5. What is the approximate distance between the object and the objective of a microscope ?

Answers :

1. When light is refracted from one medium into another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is called the refractive index of the second medium relative to the first.

The value of *r. i.* depends on the nature of the media and, to a small extenet, on the colour of light.

The yellow-green part of the spectrum to which the eye is most sensitive, (See the '*Note*' above the 'Oral questions'.)

2. The surface scratch on the upper side of the bottom marks the position of the lower surface of the liquid layer. The fine powder marks the upper surface of the liquid.

A deep scratch or coarse powder will indicate a greater thickness of the liquid layer than the real one.

3. Yes, to some extent. In measuring thin layers, the relative error is greater than for thick layers.

4. A volatile liquid quickly evaporates from its surface. So the initial thickness may diminish a little during the experiment.

5 (Look at the distance as you focus the mark when the vessel is empty, or the powder at the top.)

6-3. To determine the refractive index of a solid by the travelling microscope. Everything is the same as in the experiment just described except that a rectangular piece of the solid will replace the vessel with the liquid.

6-4. The optical bench. An optical bench in its simplest form consists of a long horizontal bed (Fig. 6.4) with several uprights mounted on it to carry the object, screen, lens or mirror. These uprights slide along the bench and may be fixed at any posi-

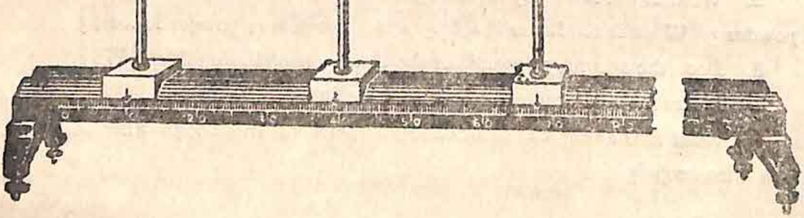


Fig. 6.4

tion. There is a mark on the base of each upright by means of which its position on the bench may be read from the metre scale fixed to the bench along its length. The object, screen, mirror or lens which the uprights carry may be fixed at any desired height.

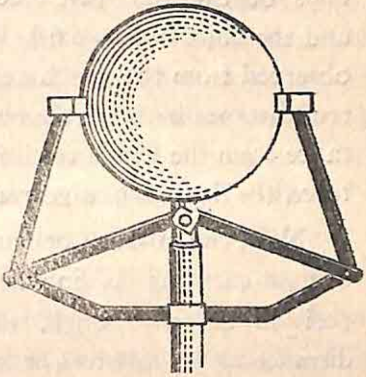


Fig. 6.5

Lenses are held in lens holders which may have various forms, one being shown in (Fig. 6.5). The object may be an illuminated slit, scratch or cross-wire. The screen on which the image is received may be of glass with lines drawn on them to judge parallax. It may also consist of a pair of cross-wires. Sharp pin-points may also be used as object and reference mark to judge parallax.

6-4.1 Index correction. When working with an optical bench we need the actual distances between the different parts, *viz.* the object, lens, mirror or screen. The distance between the index marks of the uprights carrying any two of them, say the object and the lens, may not be equal to the actual distance between them.

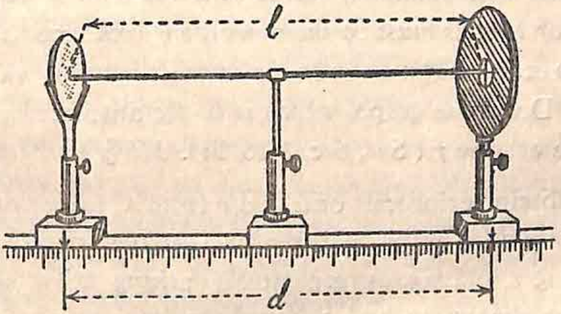


Fig. 6.6

In order to find the actual distance, an index rod of measured length, say l, is placed horizontally in between the centre of the mirror (or lens) and the object and the position of the upright carrying the mirror (or lens) or the object is adjusted until the ends of the rod just touch the surfaces of the mirror (or lens) and the object (Fig. 6.6). Let the apparent length of the rod as observed from the bench readings be d. Thus we find when the true distance between the object and the lens is l, the apparent distance from the bench readings is d. *So in order to get the true distance,* $(l-d)$ *is to be algebraically added to the apparent distance.*

Now, the mirror (or lens) or the object is rigidly fixed to the upright carrying it. So when any one of them is shifted to another position on the bench, the index mark moves through the same distance as the mirror (or lens) of the object, and the correction for getting the actual distance between them remains the same.

By using an index rod in this manner we can get the true distance between a lens or mirror and its object or image, or between an object and image formed on an optical bench.

6-5. Graphical methods of measuring the focal length. From the values of u and v obtained in an experiment, the focal length f of the mirror or lens may be determined by any of the following methods.

A. Plot corresponding values of u and v on a squared paper. *The scale of lengths must be the same along both axes and the values of* u *and* v *at the origin must be the same* ; but this value need not be zero. Draw the graph, which is a rectangular hyperbola, and from it determine f (See. Sec. 1-16, Fig. 1.2.]

B. Obtain reciprocals of u and v from a table of reciprocals. Plot points on a graph paper with $1/u$ and corresponding values of $1/v$ along x and y axes respectively taking 0—0 values for $1/u$ and $1/v$ for the origin and choosing the same unit to represent $1/u$ and $1/v$ along both axes. Draw the best straight line passing through the points. This line should make equal intercepts on both axes. The reciprocal of the intercept measures the focal length f.

[Since $1/v+1/u=1/f$, so when $1/v=0$, $1/u=1/f$, *i.e.*, the reciprocal of the intercept along the x-axis equals f. Similarly, the reciprocal of the intercept along the y-axis also equals f.]

C. Choosing the same unit of length for both u and v, measure off the corresponding values of u and v along two mutually perpendicular axes. Join the points of corresponding values by straight lines as shown in Fig. 6.7. Theoretically, all these straight lines and a straight line inclined at an angle of 45° to both axes should intersect at the same point. The projection of the point on any of the axes gives the focal length f. But in practice, due to experimental error, the points of intersection, instead of being coincident, are distributed over a region as shown in the figure. So, the mean of the projections of all the points of intersection with the straight line drawn at 45° should be taken as the focal length.

Note : The graph paper that is ordinarily used by a student in the laboratory offers a comparatively small space. This limits the scale on which u, v, $1/u$ or $1/v$ may be represented. Consequenty, the precision with which the value of f may be determinied by any of the above graphical methods is smaller than that mentioned, the method of direct calculation should be adopted by the students to find f.

Comparison of graphical methods. A straight line graph is always easier to draw than a curve. Wherever possible, graphical relations meant for calculation of a result should be presented in the form of linear relations. For a lens or mirror, B or C above is better than A for calculation. Straight lines, theoretically known to pass through the origin (0,0), are best drawn by joining the origin to the point $\bar{x}, \bar{y}$ (*mean* values of x and y). Theoretically, *this is the best straight line which the available data can give.*

A straight line graph has the further advantage that it reflects the quality of the work by the scatter of the experimental points. The closer they are to the line the better the quality.

6.6 To find the focal length of a concave mirror by the graphical method

Theory. If u and v denote respectively the object distance and the corresponding image distance, then f, the focal length, can be determined graphically in the following way (Sec. 6-5 ; Method C). v should be taken as negative when the image is virtual.

With reference to a system of rectangular axes OX and OY, the points U and V are plotted with $OU = u$ and $OV = v$ (due attention being paid to signs), and a straight line drawn from U to V. Since several observations have been made, there will be several straight lines U_1V_1, $U_2V_2 \cdots$. The coordinates (f, f) of the point of intersection of these lines give the focal length of the mirror (Fig 6.7). This point is also the intersection point with the diagonal axis.

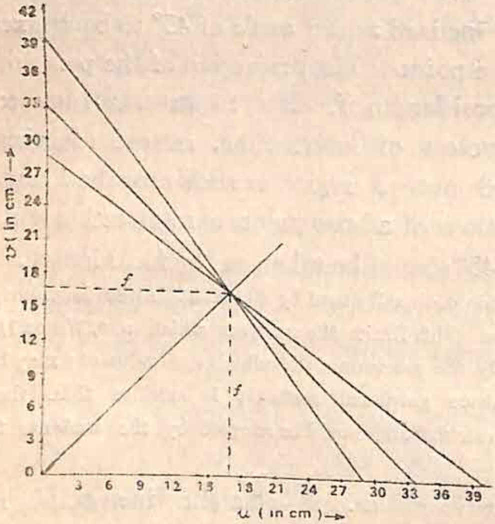


Fig. 6.7

List of apparatus. Concave mirror ; optical bench with three stands ; two pins and index rod.

Instructions. Set up three uprights, one carrying the mirror and the other two each carrying a pin. One pin serves as the object and other as the search pin. Adjust the heights of the mirror and the pins so that the axis of the mirror passes through the pin tips. Fix the upright carrying the mirror at one end of the bench and the upright carrying the object pin near the other. Look into the mirror from behind the object pin ; you will see an inverted real image, diminished in size. Adjust the position of the search pin for no parallax (See Sec. 6-1) between its tip and the tip of the image of the object pin. Read the positions of the three uprights. For each position of the object pin, find the position of the search pin thrice and take mean.

Bring the object pin closer to the mirror by steps of a few centimetres and repeat. At some stage, the object pin and the search pin will cross each other when the image will be magnified. Proceed as before till the image becomes virtual and erect.

Measure the length of the index rod by a metre scale and find index correction for u and v (See Sec. 6-41). Tabulate data as follows.

Experimental results :

Index correction for u **:**

Actual length of the index rod=……cm(l)

Distance between the index marks when the rod is placed between the object pin and the pole of the mirror=(…)—(…)=… cm (d)

Index correction for u=……cm ($l-d$)=…(i) cm.

Index correction for v :

Actual length of the index rod=…cm. (l)

Distance between index marks when the rod is placed between the search pin and the pole of the mirror=(…)—(…)=…cms (d')

Index correction for v=……cm ($l-d'$)=…i' cm.

u—v data :

No. of obs.	Position in cm of			Mean (C) cm	App. u' (B$\sim$A) cm	App v' (C$\sim$A) cm	Corrected $u=u'+i$ cm	Corrected $v=v'+i'$ cm.
	mirror (A)	Object pin (B)	Search pin (C)					
1.	…	…	(i) …					
			ii) …	…	…	…	…	…
			iii) …					
etc								

Calculation. Straight line graphs are drawn as indicated in the theory, u along the x-axis and v along the y-axis. A straight line is drawn from the origin at 45° to the axes (See 'Remark' below.)

The points of intersection of this straight line with the $U-V$ lines drawn earlier are noted in the table below ;

Curve	I	II	III	IV	V
x					
y					

Mean of the x and y values=…cm

Result : The required focal length=…cm

(Same value as the mean of x, y values).

Method followed. 1. The concave mirror and the object pin were set up at the two ends of the optical bench. The search pin was mounted in between. The heights of the pins and the mirror were so adjusted that the tips of the pins lay on the principal axis of the mirror and parallel to the bench.

2 With the help of the search pin images were located for different object distances, and the apparent values of u and v noted for real images.

3. The index corrections for u and v were determined.

4. The necessary graphs were drawn. The required f value was determined from the coordinates of the points of intersection of the u-v lines with a straight line inclined at 45° to either axis.

Remark. The points of intersection of the $U-V$ lines are supposed to give the value of f. Because of the small angles between such lines it is rather difficult exactly to locate such a point of intersection. Intersection points with the 45° are clearly defined.

Oral questions.

1. Distinguish between a real image and a virtual image ; between a real object and a virtual object.

2. Define *principal axis, focus, pole* and *aperture* of a mirror.

3. What is parallax ? Explain the method of no parallax in locating an image. Can vertical images be located by this method ?

4. Describe how the position of the image changes as the object is brought from a great distance upto the mirror along its principal axis.

5. When is the image magnified ? Erect ?

6. From which point of the mirror are you measuring distances ? What may be the error in this measurement ?

7. Does a U—V straight line express the relation between the object distance and image distance ?

Answers.

1. A real image is one formed by the *actual intersection* of rays after reflection or refraction. A virtual image is one formed by the *backward intersection* of rays after reflection or refraction. An actual body is a real object ; rays starting from it are reflected or refracted. A *virtual object* is a real image whose rays are intercepted by mirror or lens before the real image is formed.

2. (See any text book.)

3. Parallax is the relative motion between two non-coincident objects or an object and image when the eye is moved across the line joining them. (For removal of parallax, See Section 5-1.). Yes, if the image and the search pin can be seen together.

4. (See any text book. This is considered at the Higher Secondary stage.)

5. When the object is between the centre of curvature and the focus. It is erect when the object is between the focus and the mirror and also magnified.

6. Pole of the mirror. A millimetre or two.

7. No. It is a straight line *joiniug* points on the axes giving the corresponding values of u and v. Its slope gives the *magnification* v/u.

6-7. To determine the refractive index of a liquid and of the material of a convex lens using a plane mirror and a convex lens.

Theory. When a small object, such as the sharp end of a pin P_1, is placed at the principal focus of a converging lens L with a plane mirror M behind it and perpendicular to its axis (as shown in Fig. 6.8), the rays from the object after passing through the lens are reflected back on their paths to form an inverted image at the focus again. When there is no parallax between the object and the image (P_1 and P_2) both must be in the focal plane of the lens. In this way the focal length of a converging lens or a system of lesnes may be determined.

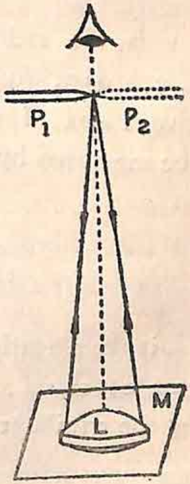


Fig. 6.8

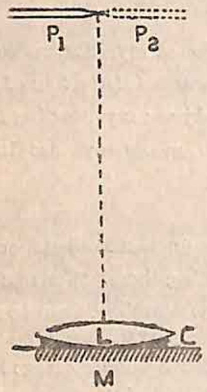


Fig 6.9

If a few drops of liquid are placed on the plane mirror and the lens over it, a plano-concave liquid lens C is formed in between the lens L and the mirror M (Fig. 6.9). The focal length f_2 of the liquid lens so formed is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}$$

$$\text{or} \qquad f_2=\frac{-f_1F}{F-f_1} \qquad (6\text{-}7.1)$$

where f_1 is the focal length of the convex lens and F that of the combination (*i.e.*, the convex lens and the plano-concave liquid lens below it), both taken positive.

The focal length f_2 of the plano-concave liquid lens is again given by

$$\frac{1}{f_2}=(\mu-1)\frac{1}{r} \text{ whence } \mu=1+\frac{r}{f_2} \qquad (6\text{-}7.2)$$

where r is the radius of curvature of the curved surface of the liquid lens (*i.e.*, lower surface of the convex lens) and μ the refractive index of the liquid. r and f_2 have the same sign. r may be measured by means of a spherometer and is given by the relation

$$r=\frac{D^2}{6h}+\frac{h}{2} \qquad (6\text{-}7.3)$$

where h is the elevation of the middle leg over the plane on which the outer legs stand and D the distance between any two outer legs forming the equilateral triangle.

Thus measuring r and f_2, μ may be determined from relation (6-7.2).

To determine the *refractive index* μ' *of the material of the convex lens*, we measure, with a spherometer, the radius of curvature r'

of the other surface of the lens (that is, the surface not in contact with the liquid). μ' is given by

$$\frac{1}{f_1}=(\mu'-1)\left(\frac{1}{r}+\frac{1}{r'}\right)$$

or, $$\mu'=1+\frac{rr'}{f_1(r+r')} \tag{6-7.4}$$

List of apparatus. Thin lens ; plane mirror ; object pin on adjustable stand ; metre scale ; spherometer ; diagonal scale and divider ; experimental liquid ; soft cloth for wiping.

Instructions. Place the convex lens on a horizontal plane mirror. Clamp a pin horizontally on a vertical stand and adjust its position such that the pin-tip lies approximately on the axis of the lens.

Look at the pin and its image from above (about 25 cm, the least distance of distinct vision) with one eye shut. Adjust the position of the lens on the mirror such that the pin-tip and its image are in the same vertical line.

Adjust height of the pin so that there is no parallax between it and its image.

Measure the distance between the pin-tip and the surface of the lens near its central region with a metre scale.

Repeat the experiment three times for three independent settings.

Remove the lens and pour a drop or two of the given liquid, the refractive index of which is to be determined, on the plane mirror and place the lens over it.

Find the focal lhngth F of the combination in a similar manner.

Clean the lower surface of the lens with which the liquid is in contact and place the spherometer on it as in Fig. 2.15. Find the elevation h of the middle leg over the plane on which the outer legs rest by taking readings on the curved surface and on the plane surface of a base plate.

Repeat your observations for h at least three times and find mean h. (See Experiment, Sec. 2-10.1.)

Place the spherometer on a clean piece of stiff paper on a drawing board with its middle leg drawn up. Press it lightly so that the outer legs imprint themselves on the paper. Measure the distances between the foot-prints by means of a pair of dividers and a diagonal scale. The mean of the three distances measures D. Calculate r from relation 6-7.3.

Thus f_2 and r being known, calculate the refractive index of the given liquid from relation 6-7.2.

Now measure r', the radius of curvature of the other surface of the lens, in the same way as for r. Apply formula 6-7.4 to find μ'.

Experimental results.

Focal lengths (f_1 and F) of the thin lens and lens combination.

No. of obs.	Distance (in cm) between pin-tip and		Focal length $f_1=\frac{L+M_1}{2}$ cm	Distance (in cm) between pin-tip and		Focal length $F=\frac{C+M_2}{2}$ cm
	convex lens (L)	mirror (M_1)		Compound lens (C)	mirror (M_2)	
1.						
2.						
3.						

Constants of the spherometer.

···full turns = ···mm
Pitch (p) = ···mm
Total circ. scale divs = ···(n)
Least count (p/n) = ···mm = ···cm

Spherometer readings and lens surface elevation (h).

Surface	No. of obs.	C. S. reading When the screw touches the lens surface (I)	When the screw touches the plate			Total no of cir. div. rotated $T=Rn+A$	value of T in mm. $T\times$l.c.	Radius of Curvatur
			nos. of full rotation of cir. disc (R)	C. S. reading (F)	additional no. of cir. div. rotated (A)			
Common lens surface (r)	1. 2. 3.						···= h	···= r
other surface (r′) of lens	1. 2. 3.						···= h′	···= r′

(*for calculation of T, see Sec. 2-10.2*)

Readings for D (distance between spherometer legs) with diagonal scale.

(*i*) ...cm ; (*ii*) ...cm : (*iii*) ...cm. Mean $D=$...cm.

Calculation and Result.

$$r=\frac{D^2}{6h}+\frac{h}{2}=\cdots\text{cm.}$$

$$r'=\frac{D^2}{6h'}+\frac{h'}{2}=\cdots\text{ cm.}$$

f_1 (focal length of glass lens) = ···cm.

F(focal length of lens combination)=···cm,

f_2 (focal length of liquid lens)$=\frac{-f_1F}{F-f_1}=\cdots$ cm.

μ (refractive index of liquid)$=1+\frac{r}{f_2}=\cdots$

μ' (refractive index of material of lens)$=1+\frac{rr'}{f(r+r')}=\cdots$

Method followed.

1. I measured the focal length of the given lens by the plane mirror and pin method.

2. I formed the liquid lens, and measured the focal length of the combined lens formed by the given lens and the liquid lens. The focal length of the combination was measrured in the same way as before.

3. Then I measured the radii of curvature of both sides of the given lens with a spherometer.

4. From the data obtained, the refractive indices of the liquid and of the material of the lens were calculated.

Remark. Both lenses were assumed thin. While this applies to the liquid lens, it is not quite true for the glass lens. To correct for the thickness of the glass lens, some teachers recommend adding *half* the thickness of the glass lens to the observed value of f_1. If such correction is at all to be made, it is better to add *one-third* of the lens thickness to the observed value of focal length. The reason for this is that for thick lenses, the simple lens formulae can be used if distances are measured from the *principal planes.* For equiconvex lenses (as laboratory lenses ordinarily are) and of refractive index

1·5 (a value good enough for use for ordinary crown glass), the principal planes are one-third the lens thickness away from a pole. *With different media on two sides of the lens, such correction should not be attempted, as the positions of the principal points change.*

6-7.1 An alternative method of finding the refractive index of a liquid. The beginner often makes a relatively large error in measuring the radius of curvature of a lens with a spherometer. By using a liquid of known refractive index (say water) the use of the spherometer may be dispensed with. For, let

f_l = the focal length of the plano-concave liquid lens of refractive index μ_l (supposed to be known),

f_s = the focal length of the plano-concave liquid lens of refractive index μ_s (to be determined),

r = radius of curvature of the curved surface of the liquid lenses.

Then $$\frac{1}{f_l} = (\mu_l - 1)\frac{1}{r}$$

$$\frac{1}{f_s} = (\mu_s - 1)\frac{1}{r}$$

whence $$\frac{f_s}{f_l} = \frac{\mu_l - 1}{\mu_s - 1}$$

From this relation μ_s may be determined since μ_l is known while f_s and f_l can be measured. The method of finding f_l and f_s has already been described in Sec. 6-7.

Oral questions.

1. What is parallax and how do you avoid it ?
2. What is the chief source of error in this experiment ?
3. Can you suggest an alternative plan by which it may be avoided ?
4. What is the nature of the liquid lens ?
5. Which is greater—the focal length of the auxiliary convex lens or that of the liquid lens ?
6. Using an equi-convex lens of refractive index 1.5, what is the maximum limit of the refractive index of a liquid for which the method is applicable ?

Answers.

1. (See Sec. 6-1, and answer to Q 3, Sec. 6-4. 1.)
2. Determination of radius of curvature with the spherometer.

3. (See Sec. 6-5.1.)

4. It is a plano-concave lens. One face (the one in contact with the plane glass plate) is plane. The liquid surface in contact with the convex lens is concave.

5. Say from your data whether f_1 is larger than f_2.

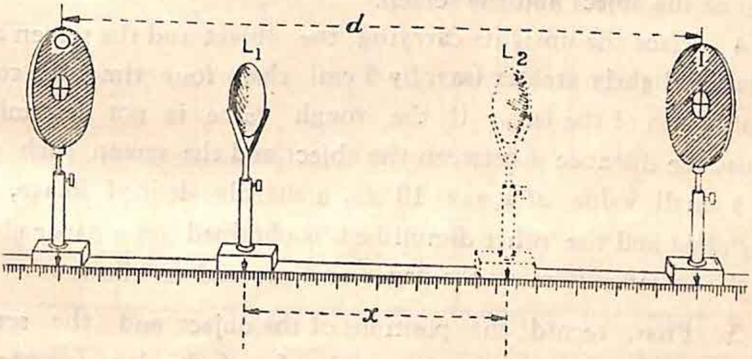
6. 2. For, let r be the radius of curvature of each face of the equiconvex lens. Then its focal length is given by $1/f_1 = (1{\cdot}5 - 1)(2/r) = 1/r$. For the plano-concave lens, the focal length f_2 is given by $1/f_2 = (\mu - 1)(1/r)$. The combined focal length F is given by

$$\frac{1}{F} = \frac{1}{r} - \frac{(\mu - 1)}{r}$$

As F must be positive (convex), we must have $(\mu - 1)$ less than 1 or μ less than 2.

6-8. To determine the focal length and power of a convergent lens by displacement method

Theory. If the distance between an object and a screen be greater than four times the focal length of a convergent lens, then for two positions (L_1 and L_2 in Fig. 6.10) of the lens, a sharply defined image of the object can be formd on the screen. The focal length f of the lens may be obtained from the formula $f = \dfrac{d^2 - x^2}{4d}$ where d is the distance between the object and the screen and x is the displacement of the lens between the two positions (L_1 and L_2.)



Pig, 6.10

The power P of the lens is given by

$$P = 100/f \text{ dioptres}$$

where f is measured in centimetres.

List of apparatus. Lens under investigation, optical bench with object and receiving screen, index rod, metre scale.

Instructions 1. Set up the object and the screen on the optical bench. Adjust their heights so that their centres stand at the same level and find the index correction between the object and the screen in the usual way (Sec. 6-4.1).

2. Try first to find a rough value of the focal length of the given lens by projecting a well-defined image of a distant illuminated object on a piece of paper placed behind the lens. Measure the distance between the paper and the lens. This gives a rough value of the focal length.

3. Set up the object, the lens and the screen on the optical bench. Adjust the heights of the uprights such that the axis of the lens is parallel to the bench and also passes through the cross-lines of the object and the screen.

4. Place the uprights carrying the object and the screen at a distance slightly greater (say, by 5 cm) than four times the rough focal length of the lens. If the rough value is not determined, adjust the distance *d* between the object and the screen such that for a small value of x, say 10 cm, a sharply defined image, one magnified and the other diminished, is obtained on a paper placed on the screen. Remove the paper and proceed as follows :

5. First, record the positions of the object and the screen. Keeping *d* fixed, determine the position L_1 of the lens (nearer the object) when a magnified image of the object is seen from behind the screen without parallax with the reference cross. Record the position of the lens upright.

6. Slide the upright carrying the lens towards the screen to the position L_2, when a diminished image will be seen. Adjust the lens for no parallax and record the new position of the lens.

7. Repeat your observation three times for each position of the lens, *d* remaining the same.

8. Increase the distance between the object and the screen by

five centimetres and repeat your observation as before. Do so for at least three different values of *d*.

As the displacement of the index mark on the upright base equals the displacement of the lens, no index correction for x is necessary.

Record your data as follows ;

Experimental results :

Index correction for d :

Actual length of the index rod$=$······cm (l)

Distance between the pointers when the rod is placed between the object and the screen$=(\cdots)-(\cdots)$

$=$······cm (l')

$\therefore$ Index correction for $d=(l-l')=\cdots(i)$.cm

No. of obs.	Position of the object (O)	Position of the screen (S)	1st Position of the lens	Mean 1st Position (L_1)	2nd Position of the lens	Mean 2nd Position (L_2)
1.	······cm	······cm	(*i*)······ cm (*ii*)······ ,, (*iii*)······ ,,	······cm	(*i*)······cm (*ii*)······ ,, (*iii*)······ ,,	······cm
2.	······cm	······cm	(*i*)······cm (*ii*)······ ,, (*iii*)······ ,,	······cm	(*i*)······cm (*ii*)······ ,, (*iii* ······ ,,	······cm
3.	······cm	······cm	(*i*)······cm (*si*)······ ,, (*iii*)······ ,,	······cm	(*i*)c······m (*iii*)······ ,, (*iii*)······ ,,	······cm

Apparent d' $(O \sim S)$	Corrected d $=d'+i$	x $=L_1 \sim L_2$	f	Mean f
···cm	···cm	···cm	···cm	···cm
··· ,,	···cm	··· ,,	··· ,,	
··· ,,	···cm	··· ,,	··· ,,	

$\therefore$ The focal length of the given convex lens$=\cdots$cm and the power of the lens$=100/f=\cdots$dioptres.

Note. 1. This method does not involve the measurement of any distance from the principal planes of the lens. Hence no correction for the thickness of the lens is necessary. It is therefore capable of giving a more accurate value than the $u-v$ method.

2. The relative error in the value of f (i.e. $\delta f/f$) is small when x is small, for it may be shown that $\delta f/f$ is proportional to $x\delta x/d$ when δx is the inaccuracy in the value of x. Further, x increases much more rapidly than d since $\delta x/\delta d=(d-2f)/x$.

These considerations show that the relative error in f will be smaller for smaller values of x. This follows easily from the relation $f=(d^2-x^2)/4d$, which shows that when x is small, f is insensitive to small variations of x.

It is therefore recommended that *the measurements should be made for values of d between 4f and 5f or so and not for much larger values.*

When x is small the inaccuracy in the setting may be large (*i.e.*, δx may be large). But even then the error is less, as the following actual data will show.

Corrected value of d	x	δx	$x\delta x/d$
65.5 cm	5.3 cm	1 cm	0.08
85.8 ,,	41.8 ,,	0.2 ,,	0.1
154.8 ,,	118.6 ,,	0.2 ,,	0.15

The lens had a focal length of 16.3 cm.

Oral questions.

1. What is the minimum distance between the object and the screen for which the method is applicable ? State reasons.

2. Why is this method superior to other methods of determining focal length ?

3. Is it better to take the distance between the object and the screen as large as practicable or small ?

Answers.

1. Calculation shows that the minimum distance between a real object and real image formed by a convex lens is four times the focal length of the lens. Hence when the object to screen distance is greater than this value, a sharp image can be formed on the screen for two positions of the lens. The object distance for one position is equal to the image distance for the other.

2. When we take thickness of the lens into consideration, the usual lens formula is applicable if distances are measured from the *principal planes* of the

lens. In this method, the question of principal planes does not arise since d is a fixed distance and x is merely a displacement. No measurement from any principal plane is involved even theoretically. So it can be applied to thick lenses.

3. A calculation of the relative error in f shows that this is lower for smaller values of x. So, the distance between the screens should not far exceed $4f$.

6-9. To determine the focal length and power of a concave lens by the combination method.

Theory. If two thin lenses are in contact, the focal length F of the combination is given by

$$\frac{1}{F}=\frac{1}{f_1}+\frac{1}{f_2}$$

where f_1 and f_2 are the focal lengths of individual lenses.

If one of them is a convex lens (of focal length f_1) and the other is a concave lens (of focal length f_2) and further, if the combination forms a converging lens, then correcting for signs, we have

$$-\frac{1}{F}=-\frac{1}{f_1}+\frac{1}{f_2}$$

or
$$f_2=\frac{Ff_1}{F-f_1} \qquad (6\text{-}9.1)$$

(Remember that under all sign conventions f_1 and f_2 have opposite signs.)

The focal length f of a converging lens may be obtained from the formula $f=\dfrac{d^2-x^2}{4d}$ where d is the distance between the object and the screen and x is the displacement of the lens for the two positions of the lens to get a sharp image on the screen.

The Power P of the lens is given by

$P=100/f_2$ dioptres,

where f_2 is measured in centimetres.

Instructions. Find by displacement method (Sec 6-8) the focal length f_1 of the convex lens (we may call if *auxiliary lens*) and the focal length F of the combination (equivalent lens) by placing the two (*i.e.* convex and concave lens) in close contact. Hence calculate f_2 and P.

Record your data as follows :

Experimental results :

Index correction for d :

Make a table as in the last expt. (Sec. 6-8)

Determination of f_1 *and* F :

Make two tables as in the last expt. (Sec. 6-8), one for f_1 and another for F.

$\therefore$ the focal length of the given concave lens $f_1 = \dfrac{Ff_1}{F - f_1} = \cdots$cm.

The power of the given concave lens $P = \dfrac{100}{f_2} = \cdots$dioptre.

Oral questions.

1. Why do you use an auxiliary convex lens ?

2. Can you find the focal length of the given concave lens by using an auxiliary convex lens of any focal length whatsoever ? State reasons.

3. Can you determine the focal length if the two lenses are separated by a distance ?

4. Will it matter if the positions of the lenses are interchanged when they are in contact or separated ?

Answers. 1. A concave lens cannot form a real image of a real object. with a suitable auxiliary lens, the combination can act as a convex lens. Real images of real objects can then be formed and the focal length of the combination determined in a straight-forward way. Using formula 6-6.1 we can then find the focal length of the concave lens.

2. The focal length of the auxiliary lens must be such that the combination can act as a convex lens. The *power* P of the auxiliary (convex) lens must be greater than the power P_x of the concave lens. The power of the combination is $P_x - P_c$; this must be positive. In other words, the focal length of the convex lens must be shorter than that of the concave lens. Otherwise, the combination will continue to act as a concave lens.

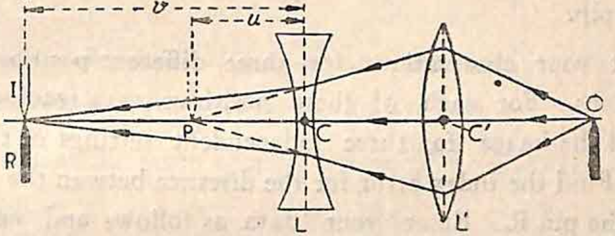
3. Yes, under proper conditions. We shall have to use a formula involving the separation. Besides, the equivalent lens must be convergent.

4. No, if we can treat the lenses as thin.

6-10. To determine the focal length of a concave lens by the auxiliary lens method

(This method is used when the auxiliary lens has a power smaller than that of the given concave lens. In such a case the two together do not form a convergent combination when in contact.)

Theory. If a beam of light converges towards a point P (Fig. 6.11) and intercepted by a concave lens, P serves as a virtual



Fig, 6.11

object for refraction by the lens. If the distance CP $(=u)$ between the optical centre C of the lens and the virtual object P is *less than the focal length (f) of the concave lens.* a real magnified image of the virtual object will be formed at I. If $CI=v$, then f is given by

$$\frac{1}{f}=\frac{1}{v}-\frac{1}{u}$$

or $$f=\frac{uv}{u-v} \qquad (6\text{-}10.1)$$

List of apparatus. Concave lens under investigation, long focus convex lens, two vertically mounted sharp pins (sharp ends preferably coloured white or yellow), metre scale (if need be).

Instructions. Set up an auxiliary convex lens (L′), an object pin (O) and a reference pin R on an optical bench. After proper adjustments find the position of the image (the position of P in this case) avoiding parallax. Read the positions of the object, auxiliary lens and the reference pin. Keeping the positions of the object and the auxiliary lens fixed, repeat your observations for three independent settings of the pin R.

Place the given concave lens, whose focal length is to be determined, between the convex lens and the image P. Adjust the height of the upright carrying the concave lens so that it is coaxial with the auxiliary lens. Hold a sighting screen near the end of the bench and adjust the position of the concave lens so that a real image is formed on it. Finally, adjust the position of the reference pin R so that there is no parallax between it and the image, now formed at I. Read the positions of the concave lens and the reference pin.

Repeat your observations for three different positions of the concave lens. For each of these positions take readings of the position of the image for three independent settings of the reference pin. Find the index error for the distance betwen the concave lens and the pin R. Enter your data as follows and calculate f from Eq. 6-10.1.

If an image is formed beyond the optical bench, use a metre scale for measuring distance.

Experimental results :

Position of the object pin=···cm

Position of the auxiliary convex lens=···cm.

No. of obs.	Position of the reference pin without the concave lens (A)	Mean $(A$	Position of the concave lens B	Position of the reference pin with the concave lens (C)	Mean (C)	Apparent u $(A\sim B)$	A ppa-rent v $(C\sim B)$
1	(i)... (ii)... (iii)...	......	....	(i)... (ii)... (iii)...	......	......	......
2	(i)... (ii)... (iii)...	......	....	(i) .. (ti)... (iii)...	......	......	......
3	(i)... (ii)... (iii)...	......	....	(i)... (ii... (iii)...	......	......	......

Index correction (which is the same for both u and v) **:**

Actual length of the index rod=······cm.

Apparent length ··· =(···)—(···)=···cm.

∴ Index correction for u or v= ……cm.

App. u	App. v	Index correction for u and v	Corrected u	Corrected v	f	Mean f
(i)						
(ii)						
(iii)						

∴ the focal length of the given concave lens = …cm.

The power of the given concave lens $=\frac{100}{f}=\cdots$ dioptres.

Oral Questions.

1, What is a divegent lens ? Are all concave lenses divergent ? Explain.

2. What kind of image does a divergent lens produce ?

3. Is the final image real or virtual in your case ?

4. How should the powers of a divergent and a convergent lens be related in order that the combination may serve as a convergent lens ?

Answers.

1, A lens that makes a parallel beam divergent or reduce the convergence of a beam is a divergent lens. All concave lenses are not divergent. If the surrounding medium has a refractive index greater than that of the material of the lens, a lens of concave shape becomes a convergent lens. Relative μ of the lens material in this case is less than 1. Hence f has the opposite sign.

2. For all real objects a divergent lens forms a virtual image. But for a virtual image between tha lens and the first principal focus, the object is real.

3. The image is real.

4. The algebraic sign of the powers should have the same sign as that of the power of a convergent lens.

6-11. The Spectrometer. It is an instrument used for the study of spectra and the measurement of refractive indices. Its essential parts are (i) the *collimator* (C, Fig. 6.12), (ii) the *prism table* (P), (iii) the *telescope* (T), and (iv) the *circular scale* (C. S., shown separately in the left inset of the figure).

(i) **The Collimator**—Its purpose is to provide a parallel beam of light. It consists of a tube with a vertical slit (S, shown separately in the right inset) of adjustable width mounted at one end of the tube and has a converging achromatic lens (O_2) at the

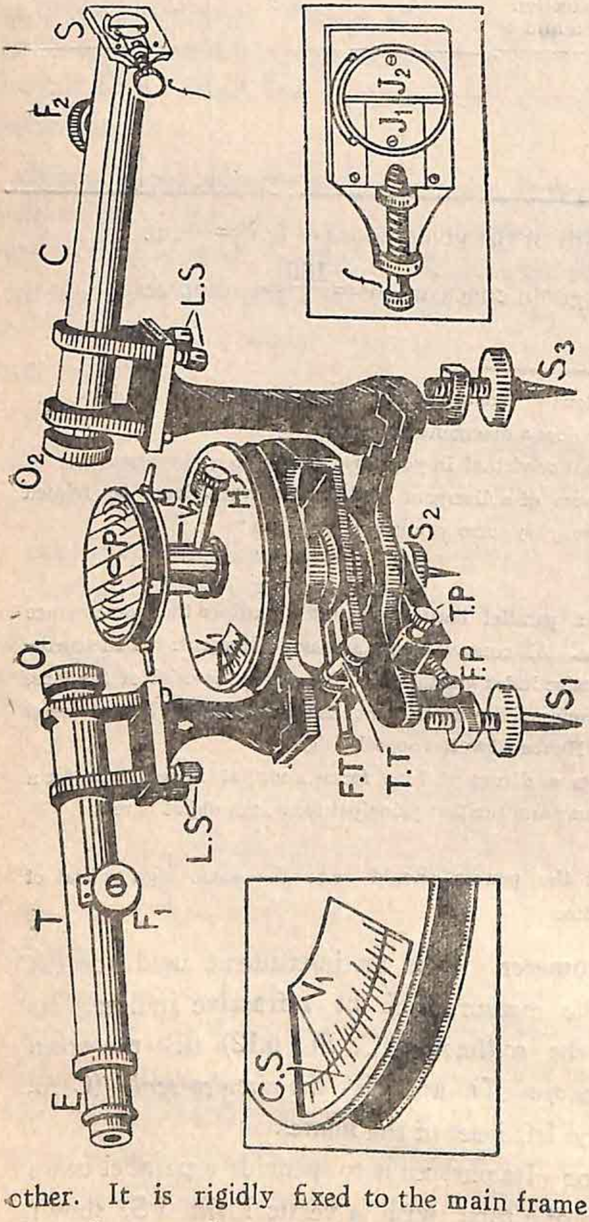


Fig. 6.12

T, telescope ; E, its eye-piece ; O_1, its objective ; F_1, its focussing screw ; C, collimator ; O_2, its lens ; F_2, its focusing screw ; S, slit ; *f*, screw for adjusting width of slit ; L.S., levelling screws ; F.T., screw for fixing telescope ; T. T., tangent screw for giving slow motion to telescope ; fixing screw for prism table ; T.P., tangent Screw for prism table ; S_1, S_2, S_3, levelling screws ; C.S., circular scale ;) V_1, V_2, vernier scales , H, screw for fixing the prism table to the verniers ; J_1, J_2, parallel jaws of the slit.

other. It is rigidly fixed to the main frame of the instrument. The distance between the slit and the lens O_2 can be altered by a rack and pinion or some other focussing device. In the figure F_2 is the focussing screw.

The slit is a very important part of the instrument. It consists of metal jaws (J_1, J_2) with exactly parallel edges. The width is adjusted by turning a screw (*f*). Light from a suitable source, such as a sodium flame, illuminates the slit. When properly focussed the slit lies in the focal plane of the collimator lens O_2. The collimator thus gives rise to a parallel beam which falls on the prism standing on the prism table. For a properly placed source the emergent beam from the collimator has a circular section of the same diameter as the lens.

(ii) The **Prism Table** has a flat top and is capable of rotation about a vertical axis. It is provided with three levelling screws. The prism is placed on the table with its refracting edge vertical.

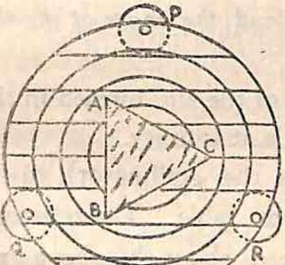
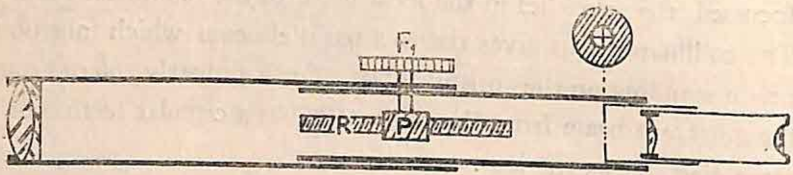


Fig. 6.13

A set of parallel, equidistant lines are ruled on the top of the prism table (Fig. 6.13). These lines are parallel to the line joining two of the levelling screws and are required for adjusting the prism. A series of circles concentric with the axis of rotation of the prism table are also ruled on the top. They help in placing the prism correctly. The height of the prism table can be adjusted. The screw H (Fig 6.12) fixes the prism table to the verniers and also keeps it at a given height.

(iii) The **Telescope** (shown separately in Fig 6.14) is an astronomical telescope. The objective is an achromatic doublet. The eye-piece is of the Ramsden type and is fitted with cross-wires. The eye-piece slides in a tube which carries the cross-wires. This tube slides in another tube which carries the objective. The distance between the objective and the cross-wires can be altered by a rack and pinion or some other focusing device. (The rack and pinion arrangement (R, P) is shown in Fig. 6.14. It should be understood that the device is on the outer side of the inner tube and does not obstruct the light.)

While working, the eye-piece is so adjusted that the cross-wires lie in its focal plane. The eye can then see the cross-wires without applying accommodation. The image of the cross-wires is formed at infinity. The focusing screw (F_1, Fig. 6.12) is then turned until there is *no parallax between the cross-wires and the image of the slit* formed by the objective of the telescope.



Fig, 6.14

The eye-piece magnifies the image of the slit formed in the plane of the cross-wires. The final image is at infinity.

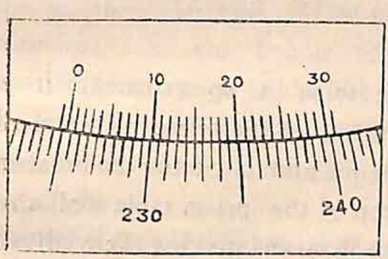
The axis of the telescope (as also of the collimator) passes through the axis of rotation of the prism table. The telescope is carried on an arm which can be rotated about the above axis of rotation (but the collimator is fixed). A counterpoise balances the weight of the telescope and eliminates the strain due to this weight on the rotation axis. The telescope and collimator tubes are supported near one end on two screws, each marked L. S. in Fig. 6.12. By means of these screws their axes may be made exactly horizontal.

The telescope may be fixed at a given position by means of the screw F. T. A slow motion can *then* be given to it by the screw T. T. called the *tangent screw*. The prism table is also provided with similar fixing and slow motion screws (F. P. and T. P. respectively). It should be noted that *a tangent screw will not function unless the corresponding fixing screw is tightened.*

(iv) **Circular Scale**—The spectormeter has a circular scale coaxial with the axis of rotation of the prism table and the telescope. It is graduated in degrees.

In some spectrometers the telescope and the prism table each carries two verniers, 180° apart, which slide alongside a fixed circular scale. In smaller instruments the circular scale and the telescope are rigidly attached to each other and turn together. Two verniers, 180° apart, are carried on a separate circular plate mounted coaxially with the circular scale. The prism table can be clamped to the spindle of this circular plate. When so clamped the prism table and the verniers turn together.

By means of the vernier the circular scale may be read up to a minute of arc or even less. As an exercise the student may try to find the reading corresponding to the zero of the vernier in Fig. 6.15. The values 230 and 240 are in degrees. The value sought may be read as 225°17′ or 225°18′. The reading is correct up to 1′.



Fig, 6.15

The purpose of having two verniers is to minimise the error due to the centre of the circular scale not lying on the axis of rotation.

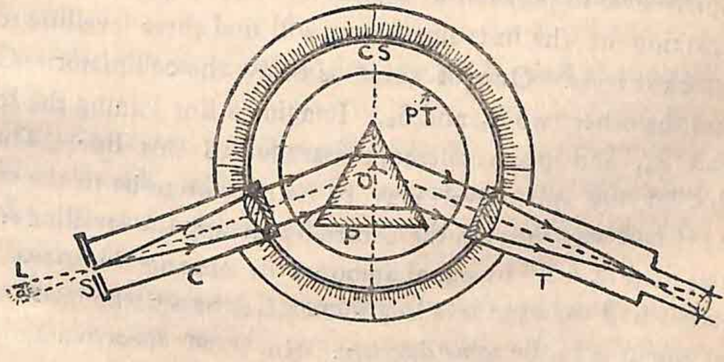


Fig. 6.16

6-11.1. Adjustments of the spectrometer. In all work with the spectrometer certain adjustments are essential. It will be advantageous to spend sufficient time over learning and practising these adjustments so that they could be completed in at most half-an-hour. The student will then have enough time at his disposal in which to take the necessary readings.

The **essential adjustments** are the following and should be performed in the given order:

(i) Levelling of the instrument (*i.e.*, of the telescope, collimator and the prism table).

(ii) Alignment of the source and screen.

(iii) Focusing of the cross-wires.

(iv) Adjustment of the slit.

(v) Focusing for parallel rays.

(i) **Levelling**. While working with a spectrometer it is necessary that (*a*) the axis of rotation of the telescope etc. shall be vertical, (*b*) the axis of the telescope and (*c*) of the collimator, shall be horizontal, and (*d*) the top of the prism table shall also be horizontal. Levelling the instrument means making these adjustments.

(*a*) *Levelling the telescope.* Place a spirit-level on the telescope taking care that its axis is parallel to that of the telescope. Fix the spirit-level in position by a piece of the string or rubber band.

Looking at the instrument you will find three levelling screws on which it rests. One of these is below the collimator. Call it S_3 and the other two S_1 and S_2. Imagine a line joining the screws S_1 and S_2, and place telescope parallel to this line. The air bubble of the spirit-level may be found not to lie in the centre. Bring it half-way towards the centre by turning the levelling screws S_1 and S_2 (Fig. 6.12) by equal amounts in *opposite directions.* For the other half turn the levelling screws L.S. below the telescope by equal amounts in the *same direction.* (In some spectrometer there may be a third screw between the screws L.S. Its purpose is to fix the telescope tube to the arm carrying it. Where this third screw is present, it should first be unscrewed sufficiently so that the screws L.S. may move easily. After the focusing has been made, the third screw may be tightened.)

Now swing the telescope so that it turns through 180° and becomes parallel to its first position. It will perhaps be found that the bubble has moved away from the centre. Bring it to the centre as before, half by S_1 and S_2 and the other half by L.S. It may be necessary to repeat the operations several times until you find that the bubble remains in the centre for both positions of the telescope. When this has been done the axis of rotations of the telescope lies in a vertical plane perpendicular to the line joining the screws S_1 and S_2.

Note that the bubble may not be in the centre for intermediate positions of the telescope. Now place the telescope in line with the collimator take the bubble to the centre by turning the third levelling screw S_3 below the collimator. This makes the axis of rotation vertical and the axis of the telescope horizontal. It is necessary to check the first adjustment after this second one has been made.

Summary. To remember the adjustments the student should mentally make a summary of them. The following may be helpful: The two positions in which the telescope is parallel to the line joining S_1 and S_2 may be called respectively the first and the second parallel positions, and the other one the perpendicular position. Then,

For the parallel positions adjust half by S_1, S_2 and the other half by L. S.;

For the perpendicular position adjust by S_3.

To facilitate work, **adjust by S_3 whenever the telescope come to the perpendicular position**, *i.e.*, in the line with the collimator.

(*b*) *Levelling the collimator.* Remove the spirit-level and place it on the collimator with the axes of two parallel. If the bubble is not in the centre, bring it there by means of the levelling screw

L. S. with which the collimator is provided. This makes the collimator axis horizontal.

(c) *Levelling the prism table.* The prism table is provided with three other levelling screws (P, Q, R, Fig. 6.13) just below it. On the table is ruled a series of lines parallel to a line joining two of these screws. Place the spirit-level parallel to these lines and bring the bubble to the centre by turning these two screws in opposite directions. Now place the spirit-level perpendicular to the lines and level it by means of the third screw. This makes the table top horizontal.

(ii) **Alignment of the source and screen.** Light the Bunsen burner and stand in front of the collimator in line with it. Look along the top of the collimator tube and *so place the burner that the axis of the collimator passes through the centre of the flame.* Place the flame at a distance of 6 to 8 inches from the slit. Once the position of the source is adjusted, take care that it is not disturbed. Lack of alignment of the source may lead to non-appearance of the image on the side.

Wind asbestos thread round an iron or copper ring of such diameter that the flame can pass through the hollow of the ring without obstruction but touch it all around. This will give a bright steady flame.

Soak the asbestos in a concentrated solution of sodium chloride. Put the ring round the flame and adjust the height of the ring such that the *brightest part of the flame lies opposite the slit.*

Now put a screen in front of the collimator and adjust the height of the aperture in it so that light from the source can reach the slit without obstruction. The purpose of this screen is to prevent light of the source from reaching the observer's eyes directly.

(iii) **Focusing the cross-wires.** Turn the telescope towards an illuminated background (a small illlumination will do). Look into the eye-piece without any accommodation in the eyes *i e*, look as you would do when you want to see a distant objects).

The cross-wires may appear blurred. Adjust the eye-piece (by moving it inwards or outwards as necessary) until the cross-wires can be seen distinctly. The cross-wires may be horizontal and vertical, or *turned through 45° with respect to the horizontal.* The authors prefer the latter position, because it is easier to set their point of intersection on the centre of the image.

(In looking into a telescope or microscope a beginner unconsciously uses maximum accommodation in the eyes. With a little practice he can learn how to use his eyes without accommodation. This is desirable as it would keep the eye free from strain and reduce fatigue. One way of doing it is to keep both eyes open and relaxed, and apply one to the eye-piece.)

(iv) **Adjustment of the slit**. Turn the telescope and bring it in line with the collimator. Looking through the telescope you will generally find a blurred image of the slit. Turn the focusing screw of the telescope (and of the collimator, if necessary) till the image of the slit appears in sharp focus. (A beginner often fails to realise the position of best focus. Remember that in this position *the width of the slit appears smallest and the boundary lines are most sharply defined.* It is advisable that you show the teacher-in-attendance the adjustment that you make.)

If the image appears not to be vertical, turn the slit in its own plane until the image is vertical. The width of the slit should be such that its image has a breadth of about a millimetre (*i e.,* about the breadth of the lead of your pencil) when held at the least distance of distinct vision. When you have acquired more skill in handling the instrument you can make the slit narrower.

(v) **Focusing for parallel rays**. There are two methods available for the purpose : *(a)* the direct method and *(b)* Schuster's method.

(a) Direct method. In the direct method the telescope is turned towards a distant object (more than 60 metres away) and focused on it. *There should be no parallax between the image and the cross-wires. This is very important.* Since the eye-piece and the cross-wires are in a separate tube and move together, the adjustment of the cross-wires is not disturbed by this focusing.*

Now bring the collimator and telescope in a straight line. The image of the illuminated slit may appear blurred. Adjust the focusing screw of the collimator untill the image of the slit, viewed through the telescope, appears in sharp focus. **There must be no parallax between the cross-wires and the image of the slit.** To test it move the eye transversely across the eyepiece. For correct adjustment there will be no relative motion between the image and the cross-wires.

In the first operation the telescope has been adjusted to bring parallel rays to a focus. In the second operation the collimator has been adjusted to produce a beam of parallel rays.

(b) **Schuster's method**. If a remote object is not available, this is the only method to be followed. Place the prism on the prism table with its refracting edge vertical. Let light from the collimator be incident on one of the refracting faces at an angle of 45° or so to the face. Close one eye, if necessary, and with the other look for the refracted beam, which is bent towards the base of the prism (Fig. 6.17) and leaves the prism horizontally. Looking into the face of the prism which the beam emerges you will see an image of the collimator lens and in its centre the bright yellow image of the slit. To see this image properly your eye should be at the same height as the centre of the prism face.

Slightly turn the prism table first in one direction and then in the other. You will find that the image of the slit moves. Now so turn the prism table that the image moves towards the side of lesser deviation. As you go on turning the prism table the image

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*Here you get an opportunity of bringing the cross-wires to the correct focus. Look at the distant object and keep both eyes open. Apply one eye to the eye-piece and adjust the latter so that you can see the cross-wires distinctly. While one eye sees the cross-wires the other sees the distant object. If both are distinctly seen the cross-wires have been correctly focused. Now bring the image of the distant object into coincidence with the cross-wires. *There should be no parallax between the two.*

moves and soon reaches a position from which it turns back. This turning point is the position of minimum deviation of the image.

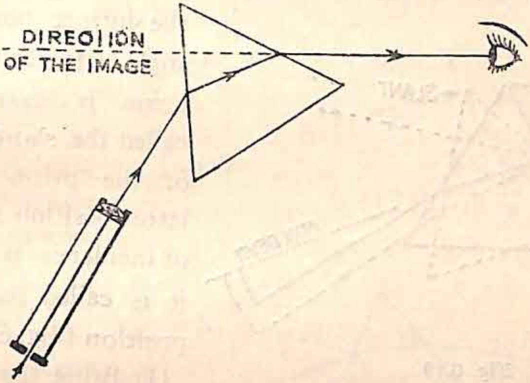

Fig. 6.17

The position of the prism in which it occurs is the *position of minimum deviation of the prism.*

Having got the image at minimum deviation with naked eyes, move your head away from the prism, still keeping the image of the slit in view. Then swing the telescope between the prism and the eye. A very small movement of the telescope this way or that will enable you to see the image of the slit in it.

Slightly turn the prism table until, on looking through the telescope, you find the image exactly at the turning point, *i.e.*, at minimum deviation. Displace the telescope a little towards the *side of larger deviation* so that the image, still at minimum deviation, lies about half to two-thirds the way down the field of view (Fig. 6 18). Whichever way you turn the prism table now, the image moves and passes the cross-wires. Thus, *there are two positions of the prism for which the image can be brought on the cross-*

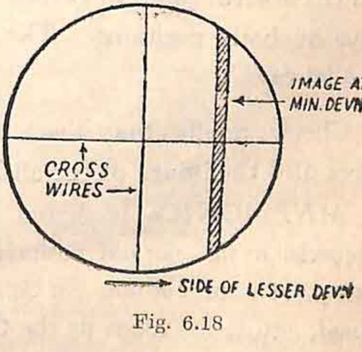

Fig. 6.18

wires. In one position the refracting edge is nearer to you than at minimum deviation. In the other position it is more remote. In the former position the angle of incidence on the prism is larger ; it is called the slant position of the prism In the latter position the angle of incidence is smaller ; it is called the normal position (Fig. 6.19).

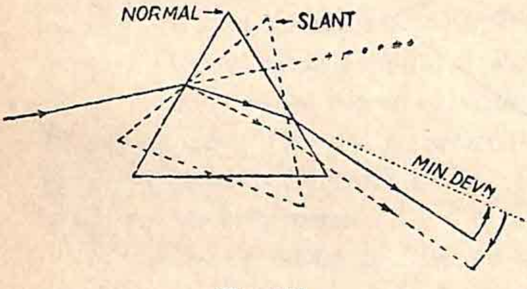

Fig. 6.19

(1) Bring the image on the cross-wires. Suppose in so doing the refracting edge has moved nearer to you than at minimum deviation. If the image is blurred focus it by the telescope, *i.e.*, the instrument nearer to you.

(2) Now turn the prism table in the opposite direction so that the refracting edge moves **away** from you. The image moves towards the position of minimum deviation, turns back and reaches the cross-wires again. If the image is blurred focus it by the collimator, *i.e.*, the instrument **away** from you.

In general, it will be necessary to repeat the operations (1) and (2) several times in succession until the image appears in sharp focus at both positions. The spectrometer is then focused for parallel rays.

Check finally that there is no **parallax between the cross-wires and the image of the slit.**

*MNEMONIC** It should be noticed that *the focused image is broader in the normal position and narrower in the slant position.* This gives a mnemonic for Schuster's method : When the image is Broad, adjust the focus by the Collimator, or more simply, Broad—Collimator. There is also another way of remembering : adjust the focus by the instrument nearer to or away from you according as the refracting edge has moved nearer to or away from you (or more simply, *near—near, away—away*).

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*Aid to memory.

Theory of Schuster's method. When a narrow beam of light, coming from a point object, is refracted through a prism, the emergent beam appears to come from a point image. If the mean ray of the beam passes through the prism at minimum deviation the distance of the image from the prism is equal to the distance of the object. But when the angle of incidence is smaller than that at minimum deviation, the image is nearer than the object. For angles of incidence larger than those at iminimum deviation, the image is farther than the object.

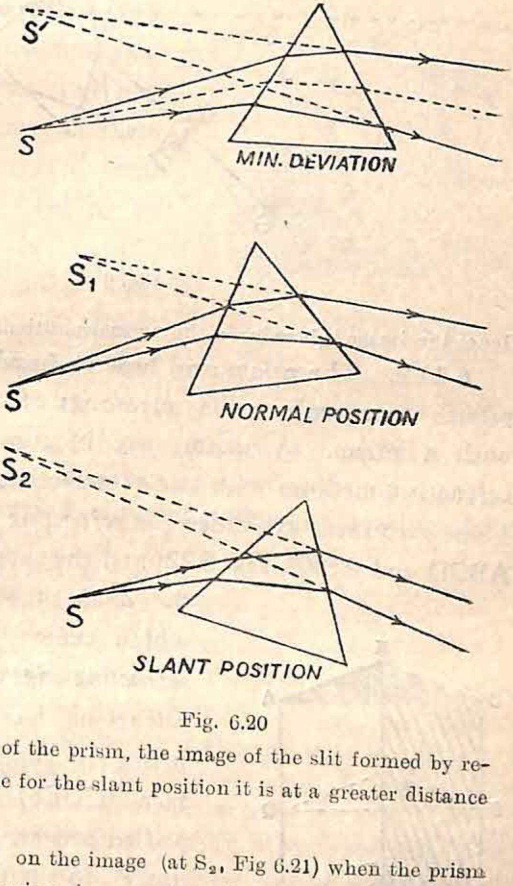


Fig. 6.20

Thus, for the normal position of the prism, the image of the slit formed by refraction at the prism is nearer, while for the slant position it is at a greater distance (Fig. 6.20).

Suppose the telescope is focused on the image (at S_2, Fig 6.21) when the prism is in the slant position. Let the prism be now turned to the normal position. Since the image moves nearer (at S_1), it will be out of focus in the telescope. By moving the collimator lens nearer to the slit this image at S_1 is pushed to the previous point of focus S_2 of the telescope. If now the prism is changed in position from normal to slant, the image moves farther. The telescope is focused on this more remote point.

In this way the point on which the telescope is focused moves away to greater distances with every adjustment of the telescope. The collimator pushes the image at the normal position to the position of the image at the slant position. When finally both images are formed at very great distances they appear to be in focu for both positions of the prism.

The magnification of the image is greater for smaller angles of incidence.

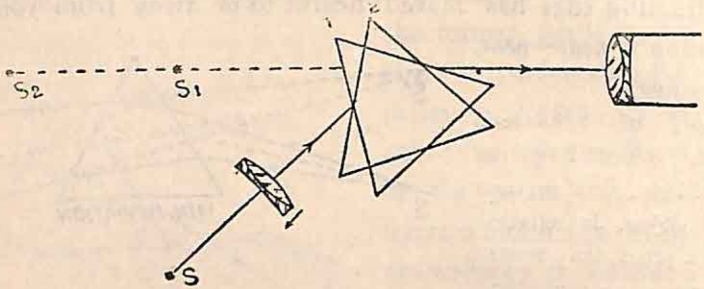


Fig. 6.21

Hence the image is broader in the normal position.

6-11.2. The prism and how to handle it. It may be worth while to remember the meanings of terms used in connection with a prism. A prism may be considered to be a portion of a refracting medium with two intersecting plane boundary surfaces. These two faces are called the *refracting faces* of the prism (faces ABCD and ABFE, Fig. 6.22) and the angle between them is called the *angle of the prism*. The line along which these planes intersect is the *refracting edge* of the prism (line AB). The refracting faces are well polished. The prism is generally limited by a third face (CDEF) which, except in right-angled prisms, is generally set at the same angle to both refracting faces. This face is the *base* of the prism. It is generally not polished and can thus be easily distinguished from the refracting faces.

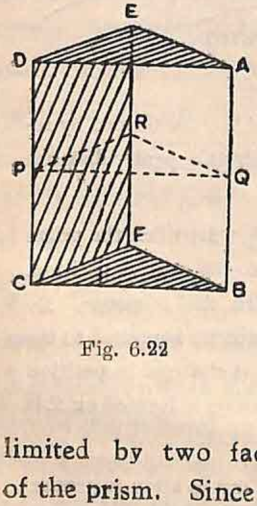


Fig. 6.22

On the other sides the prism is limited by two faces (CBF and DAE) perpendicular to the edge of the prism. Since no refraction occurs through them they are also not polished. The prism rests on one of these faces.

A section of the prism perpendicular to the refracting edge is called a *principal section* (PQR). In the elementary theory of the prism the incident and refracted rays are supposed to be confined to the same principal section.

When using a prism take care that its refracting faces are perfectly clean and have no trace of grease on them. Soft linen moistened with alcohol may be used to remove the grease.

In handling a prism don't grab it by the sides. *Always hold it between fingers by the top and bottom.* To lift it tilt it in the manner indicated in Fig. 6.22 (*a*). While placing it on a table proceed similarly.

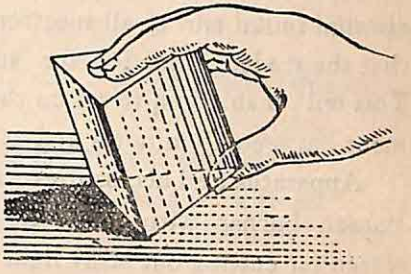


Fig. 6.22 (*a*)

In cheap prisms, the refracting faces are not quite plane. They produce distorted (curved) images of the slit. Such prisms should not be used.

6-11.3. **Optical levelling of a prism.** When working with a prism it is necessary that its refracting faces should be vertical. If the bottom section is perpendicular to the faces, levelling the prism table automatically brings about this adjustment. But slight differences generally remain and may be removed by optical levelling. The operation is as follows :

Place the prism on the prism table so that one of the refracting faces is at right angles to the line joining two of the levelling screws of the prism table. (In Fig. 6.13 the face AB is shown placed perpendicular to the line QR). It will generally be found convenient to place the apex of the prism at the centre of the table.

Turn the telescope so that its axis makes an angle of about 90° with the axis of the collimator. Then turn the prism table till you see in the telescope an image of the slit produced by light reflected from the face AB (*i.e.*, the face which is perpendicular to the line joining two of the levelling screws). If the image is not central in the field of view (judged vertically), bring it to the centre by turning the above levelling screws (in opposite directions). Then turn the prism so that light reflected from the face AC enters the telescope. If the image is not central, make it so by turning the third levelling screw of the prism table.

The first operation makes the face AB vertical. The second operation turns AB in its own plane but does not alter its adjustment, while it makes the face AC vertical. The two operations together constitute optical levelling.

6·12. An auxiliary experiment :

To set up a spectrometer and adjust it for parallel rays.

[Note : This is not a prescribed experiment. But it is the *essential initial part* of all spectrometer experiments. It is advisable that the student practises the adjustments for two working days. This will enable him to set up the apparatus for any later experiment between 15 minutes and at most half an hour.]

Apparatus and accessories. Spectrometer ; spirit level ; prism ; Bunsen burner with salt ring to produce monochromatic light ; screen for cutting out stray light from source ; reading lens.

Procedure to follow (or Instructions).

The essential adjustments are the following and should be performed in the given order (See Sec. 6-11.1) :

1. *Levelling the instrument* (that is, of the telescope, collimator and the prism table).

These have been discussed in Sec. 6-11.1 under the head 'Levelling'. See the portions (*b*) and (*c*) at that place and the 'Summary' of portion (*a*).

2. *Alignment of the source and screen.*

See portion marked '(ii)' with this heading in Sec. 6·11.1.

3. *Focusing the cross-wires.*

See portion marked '(iii)' with this heading in Sec. 6-11.1

4. *Adjustment of the slit.*

See portion marked '(iv)' with this heading in Sec. 6-11.1

5. *Focusing for parallel rays.*

See portion marked '(v)' with this heading in Sec. 6·11.1. Practise Schuster's method. Remember the *Mnemonic* (=aid to memory) given there.

6·13. To adjust a spectrometer for parallel rays by Schuster's method and to determine the refractive index of the material of a prism by minimum deviation method.

Theory. Let A be the angle of the prism and δ the minimum deviation which light of a given colour undergoes by refraction through the prism in a principal section. Then the refractive index of the material of the prism for light of the given colour is obtained from the relation

$$\mu=\frac{\sin\frac{1}{2}(A+\delta)}{\sin\frac{1}{2}A}$$

List of apparatus. As in Sec. 6-12.

Instructions. A. Make adjustments 1 to 5 as indicated in Sec. 6-12.

B. *Vernier constant.* Next, determine the vernier constant of the circular scale. Remember that the scale is graduated in degrees and fractions thereof. Express the vernier constant in minutes or seconds (but not in fractions of a degree).

C. *Angle of the prism.* There are *two methods* for measuring the angle of the prism. One of them involves measuring the angle of rotation of the prism table, and the other—of the telescope.

Place the prism with one of its refracting faces (call it AC) perpendicular to the line joining two of the levelling screws of the prism table (say, to the set of parallel lines drawn on the prism table. See Fig. 6. 13). *The vertex of the prism should be at the centre of the prism table.*

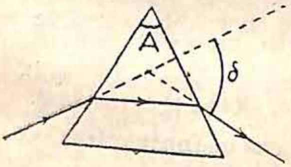


Fig. 6.23

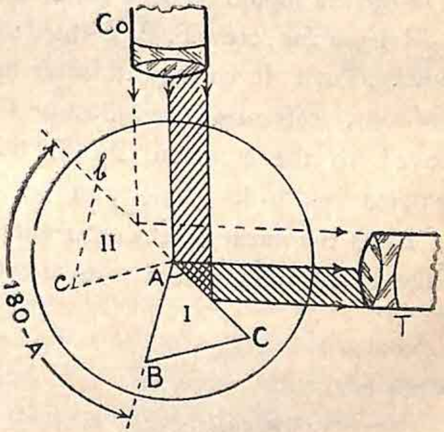


Fig. 6.24

Place the telescope at an angle of about 120° to the collimator. (This setting is not at all critical. The value may be anything between 90° and 120°, but the higher value is preferred because the image will be brighter.)

Method 1.—If the prism table has no vernier permanently attached to it, fix the axis of the prism table to the spindle of the disc which carries the vernier. (This is done by the screw H of Fig. 6.12.)

Turn the prism table until an image of the slit formed by light reflected from the face AC can be seen in the telescope. (If necessary, level the prism optically See Sec. 6-11.3.)

Set the junction of the cross-wires at the centre of the image. This can be done by fixing the telescope in position (screw F. T. of Fig. 6.12) and working its tangent screw T. T. Read the verniers (of the prism table).

The prism table may now be slightly disturbed and the image set on the cross-wires again. But this time the fine adjustment should be made by fixing the prism table by means of the screw F.P. (Fig 6.13) and working its tangent screw T. P. The operation of re-setting should be done thrice and the verniers read each time.

Release the screw F. P. so that the prism table is now free to move. Turn it so that an image of the slit is again seen in the telescope, this time by reflection from the face AB which has moved to the position *Ab* (Fig 6.24). Note that the telescope remains fixed in its former position.

Bring the image on the cross-wires as before. Read the verniers. Take three independent sets of readings in the manner already described.

The angle by which the prism table has turned between the two positions is equal to 180° $-A$.

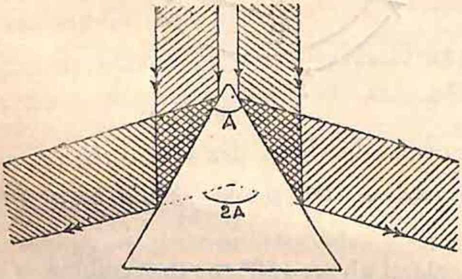


Fig. 6.25

Method 2.—In this method the beam from the collimator is allowed to fall simultaneously on both refracting faces of the prism and is reflected therefrom

(Fig 6 25). The telescope is set successively to receive the reflected beams, the centre of the image being brought into coincidence with the junction of the cross wires at both positions. The angle by which the telescope turns between the two positions is twice the angle of prism (Fig. 6.26)

Note that in this method the prism table remains fixed in position while the telescope moves. In Method 1, the telescope remains fixed in position, while the prism table moves. In either method the instrumet which does not move should be kept fixed to the body by means of the respective fixing screw. For fine adjustment the tangent screw of the other should be worked.

In both methods the vertex of the prism should be at the centre of the prism table. If the source is not properly aligned you may fail to get one of the images.

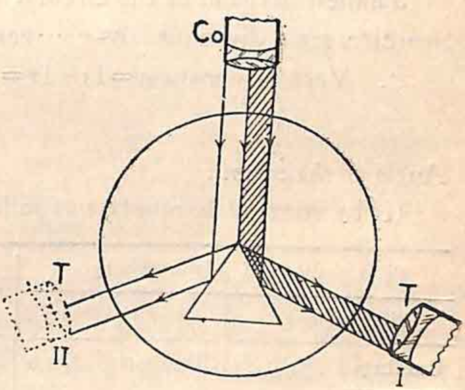


Fig. 6.26

D. *Angle of minimum deviation.* Adjust the prism so that the deviation is a minimum. The prism should be so placed that it receives the maximum light from the collimator while the plane bisecting the vertical angle of the prism passes through the axis of rotation of the prism table. The circle drawn on the prism table helps in this adjustment. This position is totally different from the position in which the prism was placed in finding the angle. Fix the prism table.

Having got the image exactly at the position of minimum deviation, set the cross-wires at the centre of the image. Read both verniers (the telescope verniers if they are separtae). Take three independent sets of readings.

Remove the prism, but don't disturb the prism table. Place the telescope in a straight line with the collimator and take the direct reading. The difference from the previous reading gives angle δ.

Experimental results :

Vernier constant :

Smallest division of the circular scale=……min.

……circ. scale divisions (s)=……vernier divisions (v).

$\therefore$ Vernier constant$=1s-1v$=……main scale division.

=……minutes (or seconds)

Angle of the prism :

(If by Method 1, tabulate as follows :)

First position of prism table by				Second position of prism table by			
First vernier		Second vernier		First vernier		Secend vernier	
Readings	Mean	Readings	Mean	Readings	Mean	Readings	Mean
………		………		………		………	
………	………	………	………	………	………	………	………
………	(a_1)	………	(b_1)	………	(a_2)	………	(b_2)

180°—A			$A=180°-c$
Ist vernier	2nd vernier	Mean	
$a_1 \sim a_2$	$b_1 \sim b_2$	$(a+b)/2$	
$(=a)$	$(=b)$	$(=c)$	………

(If by Method 2, write 'telescope' for 'prism table' and $2A$ for 180°—A in the tables.)

Angle of minimum deviation :

Readings of telescope at minimum diviation by				Direct readings by			
First vernier		Second vernier		First vernier		Second vernier	
Readings	Mean	Readings	Mean	Readings	Mean	Readings	Mean
…………	………	…………	………	…………	………	…………	………
…………	………	…………	………	…………	………	…………	………
…………	(d_1)	…………	(d_2)	…………	(f_1)	…………	(f_2)

	1st vernier	2nd vernier	Mean
Value of δ	$d_1 \sim f_1$	$d_2 \sim f_2$	

$$\therefore \quad \mu = \frac{\sin \frac{1}{2}(A+\delta)}{\sin \frac{1}{2} A} = \frac{\sin\cdots\cdots}{\sin\cdots\cdots} = \cdots\cdots$$

[*N. B.* In measuring A and δ it sometimes so happens that the zero of the circular scale is crossed in going from one position to the other. In case this happens the actual angle turned through is obtained by adding 360° to the lower value and subtracting the higher value from the sum.

Suppose in measuring A by method 2 (the split beam method) the values are found to be 290° and 50°. The zero of the scale has been crossed in this case. The value of the angle turned through by the telescope is (360°+50°)—290°.

The student should carefully note whether he cross the zero of the circular scale while measuring a rotation.]

Precautions.

(i) There must be no parallax between the cross-wires and the image of the slit.

(ii) The source must be properly aligned.

(iii) While measuring the angle of the prism the vertex of the prism should be placed at the centre of the table.

Method followed : (A brief statement)

[In your record you may write as follews :]

1. The spectrometer was levelled in the usual way so as to make (*a*) the axis of rotation of the telescope vertical, (*b*) the axis of the telescope and collimator horizontal and (*c*) the top of the prism table horizontal.

2. The sodium flame was placed at a distance of about 8″ from the slit (so as to fill completely the aperture of the collimator lens). The axis of the collimator passed through the centre of the flame. The salt ring was so placed that the brightest part of the flame was opposite the slit.

3. The eyepice was focused on the cross-wires, the eye being at rest (*i.e.*, free from strain). The cross-wires were vertical and horizontal (or turned through 45° to the vertical).

4. The slit was made vertical and narrow.

5. The telescope and collimator were adjusted for parallel rays by Schuster's method.

6. There was no parallax between the cross wires and the image of the slit. The cross-wires were set at 45° to the horizontal.

7. The vernier constant of the circular scale was determined.

8. The angle of the prism was determined by keeping the telescope fixed in position (Method 1)/prism fixed in position (Method 2).

9. The angle of minimum deviation was then measured.

Oral questions (on adjustment of the spectrometer).

1. What are the essential adjustments of the spectrometer ? State briefly how they are made.

2. What is the harm if (*a*) the source does not lie on the axis of the collimator, (*b*) the spectrometer is bodily tilted after it has been levelled, (*c*) no adjustment for

parallel rays is made, (*d*) the slit is not vertical, but the refracting edge of the prism is so ?

3. State briefly the theory of Schuster's method.

Answers. 1. (See Sec. 6-11.1. Briefly state the contents of portions marked (*i*) (*ii*), (*iii*), (*iv*) and (*v*) of that section.)

2. (*a*) The collimator lens may not get any light at all, or get it so partially and at such an angle that we may fail to get the image in the telescope.

(*b*) The source will not remain properly aligned, and the difficulties mentioned in (*a*) above will appear.

(*c*) When focused for parallel rays. the rays through the prism are also parallel. When *not* focused for parallel rays, a divergent beam passes through the prism. The angle of divergence is different for different positions of the virtul image formed by the prism. The angles of emergence therefore differ.

(*d*) Different parts of the image will have different deviations.

3. See 'Theory of Schuster's method' at the end of Sec. 6-11.1.

Oral questions. (on determination of r.i. of prism).

1. What do you mean by (*a*) the principal section, (*b*) the refractimg edge and (c) the base of a prism ?

How does a ray pass through a prism at minimum deviation ? Which of the ollowing statements is more correct—(*a*) the ray passes parallel to the base, or f(*b*) the ray passes perpendicular to the plane bisecting the angle of the prism ?

3. How did you place the prism when measuring (*a*) the angle of the prism. (*b*) the angle of minimum deviation ?

4. What is it that you see in the telescope ? Is the image real or virtual ? Where is it situated ?

5. Why should there be no parallax between the cross-wires and the image ?

6. For what colour have you detemined the wavelength ? Would it be different if white light were used ?

Answers.

1. (See Section 6-11.2)

2. We say that the ray passes *symmetrically* through the prism, thereby meaning that it is perpendicular to the plane bisecting the angle of the prism. Only when the prism is isosceles, the ray is parallel to the base. Statement (b) is more correct.

3. (*a*) The vertex of the prism at the centre of the prism table. (*b*) The centre of the base at the centre of the prism table.

4. The image of the slit. It is virtual. At infinity, if the telescope is focused for infinity.

5. If there is parallax the reading (of the telescope) will be in error.

6. For sodium light (wavelength 5893 Å). White light would give a continuous spectrum. R. i. for different parts of the spectrum are different.

6-14. To find the refractive index of the material of a thin prism by the method of normal incidence

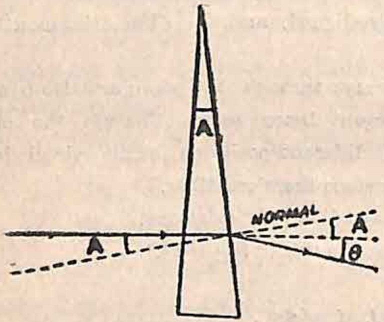


Fig. 6.27

Theory. Let a ray of light be incident normally on one face of a thin prism, and emerge out of the other with a deviation θ (Fig. 6.27). Then the angle of emergence is $A+\theta$ where A is the angle of the prism. The corresponding angle of incidence within the prism is A.

Since the path of a ray is reversible, a ray of light incident on the prism at angle $A+\theta$ will be refracted into the prism at an angle A. Hence by definition the refractive index of the material of the prism relative to the outer medium is given by

$$\mu=\frac{\sin(A+\theta)}{\sin A} \quad \cdots \quad (6\text{-}14.1)$$

[*Note.* If the angle of prism were very small making $A+\theta$ smaller then 5°, the sine values may be replaced by the values of the angles. The error involved in such substitution is about 1 part in 900.]

List of apparatus. Spectrometer, spirit level, an ordinary prism for focusing by Schuster's method, the experimental prism, a reading lens, etc.

Instructions. Make adjustments (1) to (5) as detailed in Sec. 6-12. Find the vernier constant. Take the direct reading. Turn the telescope exactly through 90° and fix it there.

Cleanse the thin prism if necessary. Place it with its apex over the centre of the prism table and one of the refracting faces perpendicular to the line joining two of the levelling screws of the prism optically (see Sec. 6-11.3).

Angle of the prism. If the prism table has no separate verniers, attach the table to the spindle of the disc carrying the verniers. Find the angle of the prism by Method 1 elaborated in Sec. 6-13. Take care not to alter the position of the telescope in any way.

Setting the prism for normal incidence. Push the prism parallel to itself over the centre of the table so that it intercepts maximum light from the collimator. Now, rotate the prism table until you see in the telescope an image of the slit formed by reflection from one face of the prism. Bring the centre of the image on the junction of the cross-wires. The necessary fine adjustment should be done by fixing the prism table and working its tangent screw. Read the position of the verniers. Note that this makes the incidence on the receiving face of the prism exactly equal to 45°.

Release the fixing screw (F. P.. Fig. 6-12) of the prism table. Turn the prism table along with the verniers exactly through 45° in the proper direction so that the face of the prism which received the light is now exactly perpendicular to the incident beam. Keep the prism table fixed in this position.

Angle of deviation. Release the telescope and bring it almost in line with the collimator. You may see two images, one formed by light from the collimator reaching the telescope directly if the prism is not large enough to intercept the entire beam. The other image is the refracted image and lies on the same side of the former image as the base of the prism. Set the junction of the cross-wires at the centre of the second image and take the reading of the verniers. The fine adjustment should be done by working the tangent screw of the telescope. The prism table should not be disturbed in any way.

Now remove the prism without altering the position of the verniers. Take the direct reading. The difference between this value and the previous one is the value of θ. (Note that unless the scale is fixed the first direct reading and this one will not agree)

Experimental results :

Vernier constant :

Smallest scale division ot the circular scale=···min
···circular scale divisions=···vernier divisions.
∴ Vernier constant=···(minutes or seconds).
Direct reading=···(a) [Read one vernier only.]
Telescope set at ($a \pm 90°$), *i.e.*, at······

(The value 90° is to be added or subtracted according to the direction in which the telescope is turned.)

Angle of the prism (A) ;
[Make table as in Sec. 6-13.]
Angle of deviation (θ) :
[Make table as in Sec. 6-13.]

$$\mu = \frac{\sin (A+\theta)}{\sin A} = \frac{\sin\cdots\cdots}{\sin\cdots\cdots} = \cdots\cdots$$

Precautions. As in Sec. 6-13.

Method followed :

[Write it as in Sec. 6-13.] But after item 7, add (8) The telescope was fixed at 90° to the direct beam.

(9) The angle of the prism was determined, and the prism set for normal incidence.

(10) The telescope was then released and the angle of deviation measured.

Oral questions.

1. What is a thin prism ? For determining r.i. of the material, has it any advantage over a larger angled prism ?

2.. How do you find the angle of incidence in this case ?

3. Is there only a single value of the angle of incidence corresponding to a given angle of deviation ?

4. How does deviation depend on the colour of light ?

5. Could you have used white light for your experiment ?

6. Why do you use a sodium flame ?

7. What is the wavelength of the light for which you have measured the r.i. ?

Answers.

1. A prism of which the vertical angle is small is called a thin prism. For measuring r.i., it has no material advantage over a larger angled prism. When $A<5^\circ$ or so we may write $\sin A=A$ and $\sin\theta=\theta$, correct to within about 1 part in 1000. When $A+\theta$ does not exceed this value, the deviation $\theta=(\mu-1)A$ is practically independent of the angle of incidence, which must be near normal.

2. (Say how you did it. The incidence was normal.)

3. Unless the deviation is minimum, there are two angles of incidence for which the deviation is the same.

4. Deviation increases slightly with increase in μ. Hence shorter light-waves (violet, blue etc.) are more deviated than longer wave (red, orange, etc.).

5. No, different colours will be differently deviated.

6. To get monochromatic light.

7. 5893 Å—the mean wavelength of sodium light.

6-15. To plot the incidence-deviation curve and hence to find the angle of minimum deviation of a prism

Theory. The deviation which a ray of light undergoes on refraction through a prism depends on the angle of incidence, the angle of the prism, the refractive index of the material of the prism and the colour of light. If the angle of incidence is changed keeping other factors constant, the deviation also changes and passes through a minimum.

List of apparatus. As in Sec. 6-12.

Instructions. Make adjustments (1) to (5) of the spectrometer as detailed in Sec. 6-12. Find the vernier constant Remove the prism. If the prism table has no separate verniers, *detach the prism table* from the vernier so that the former can be moved without moving the latter. *Fix the verniers* (screw F. P., Fig 6-12). Take the direct reading. Call it *D*. This value plus or minus 180° gives the position of the collimator. Call it *C*.

Cleanse the faces of the prism (with a soft piece of cloth), if necessary. and place the prism on the prism table with one of the refracting faces perendicular to the line joining two of the levelling screws of the prism. Further, the plane bisecting the vertical angle of the prism should pass through the axis of rotaion of the prism table while the vertex of the prism should not be more than, say, one centimetre away from the axis. This will enable you to see both the reflected and the refracted images without difficulty. Level the prism optically, if necessary (Sec. 6-11.3).

Slowly rotate the prism table to more slant positions and look for the refracted beam with naked eyes. Reach the position at which the refracted ray emerges almost grazing the surface (Fig. 6.28). Rotate the telescope to receive this image on the cross-wires and read the (telescope) verniers. Call it R_1.

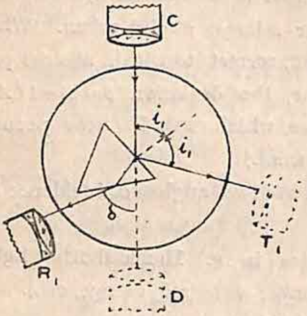


Fig. 6.28

Turn the telescope towards the side of the vertex of the prism so as to receive the reflected image on the cross-wires. Read the position of the telescope. Let it be r_1.

Then the difference of C and R_1 is the angle of deviation and half the difference of C and r_1 is the corresponding angle of incidence.

Move the telescope about 10° towards the collimator. Turn the prism table so as to throw the reflected image into the telescope. Get the image on the cross-wires and read the position of the telescope. Let it be r_2. The angle of incidence has now diminished by half the difference of r_1 and r_2. The new value is $\frac{1}{2}(C \sim r_2)$.

Without disturbing the prism table rotate the telescope to receive the refracted image on the cross-wires and take the reading. Let it be R_2. Then the angle of deviation corresponding to the altered angle of incidence is $D \sim R_2$.

In this way go on moving the telescope nearer to the collimator by steps of about 10°, and for each setting of the telescope read the position of the refracted image. Carry on the observations until you fail to get either the reflected or the refracted image.

Calculate the corresponding values of the angles of incidence (i) and deviation (δ). Plot the graph of δ against i as the independent variable.

Experimental results :

Vernier constant : (As in Sec. 6-13)

Direct reading (C) = …… (in deg., min, and sec.)

$\therefore$ Reading corresponding to incident beam

$= D + 180^\circ$ or $D - 180^\circ = \cdots\cdots\cdots (C)$

Readings for			
reflected image (r)	refracted image (R)	i $= (C \sim r)/2$	δ $= D \sim R$

Draw graph of δ against i. (The nature of the graph is shown in Fig. 6-29.)

From the graph, the minimum value of $\delta = \cdots\cdots\cdots$

and the correspoding value of $i = \cdots\cdots\cdots\cdots$

Precautions.

1. The source must be properly aligned.
2. There must be no parallax between the cross-wires and the image of the slit.
3. To get the image exactly on the cross-wires work the tangent screw of the telescope.
4. The prism table must not move until both the angle of incidence and the corresponding angle of deviation have been measured.

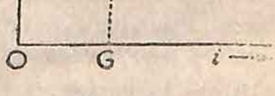


Fig. 6.29

5. Where the scale moves with the telescope the verniers must remain rigidly fixed. If the scale is fixed the verniers of the telescope are to be read.

Method followed :

[Record item 1 to 7 as in "Method followed" under Sec. 6·13.]

8. The direct reading was taken. The centre of the base of the prism was placed on the centre of the prism table.

9. Starting from nearly grazing angle of emergence, the image positions were determined at intervals of about 10° and readings of the telescope taken to find δ.

10. For each δ, the telescope was turned to receive the reflected image on the cross-wires and the readings taken.

11. From the set of i, δ values so obtained, the i—δ graph was drawn and the value of minimum δ determined.

Oral questions.

1. Is it always possible to get a refracted ray through a prism ?

2. What is a total reflection prism ? Can you get a refracted ray through it ?

3. When a beam of light falls on one face of a prism what happens to it ? Is it wholly refracted ?

4. Will there be an emergent ray if light falls on one face of a 60° prism at right angles to the face ?

5. In this experiment you are using the formula for refraction at a single surface. Is a prism essential for the work, or could you have used a glass plate with parallel faces ?

Answers.

1. It may not be possible. If the angle of incidence on the second face (inside the glass) is greater than the critical angle, there will be no emergent ray. The ray incident on the surface will be totally internally reflected.

2. Ordinarily it is a right-angled isosceles prism. A ray entering it through any of the shorter sides is totally internally reflected from the hypotenuse face. If incident normally on the hypotenuse face, it is totally internally reflected successively from the other two faces and comes out through the hypotenuse face.

3. At each air-glass surface a part of the incident light is reflected and a part refracted (except when total internal reflection occurs). Amount of reflected light increases with the angle of incidence.

4. No emergence from the second (refracting) surface. The light falls at 60° incidence on the second face and is totally reflected towards the base.

5. When a parallel glass plate is used, the emergent ray is parallel to the incident ray. A spectrometer cannot measure the angle of refraction within a parallel glass plate.

6-16 To measure a small angle using a scale and telescope. In the next two experiments you will be required accurately to measuse small angles, smaller than a degree. The angles are the angles between two positions of a spectrometer telescope. The measurement can be made with the help of a scale and another telescope.

Mount a piece of plane mirror vertically on a cork. Attach the cork with a little bees-wax on the tube of the spectometer telescope.

Hold a lamp near the plane mirror and look for its image in the mirror. Now gradually move away from the mirror in a direction normal to it, but never lose sight of the image of the lamp. If the image tends to go out of the field of view in a vertical direction, alter the tilt of the mirror. The lamp should be close to the eye and shaded from the eye. In this way move as far back as you can. Stop at a distance of about 2 metres, preferably more if you have space. Clamp the lamp to a stand at the place you last held it. Take a telescope on stand with a paper scale mounted horizon-

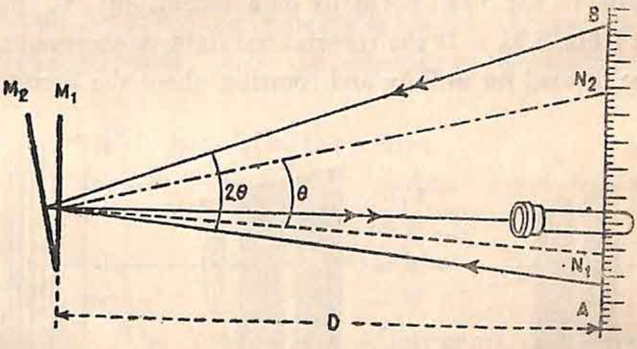


fig. 6.30

[Scale-and-telescope arrangement. When the mirror is at M_1, N_1 is on the normal to the mirror. As M_1 turns through θ to M_2, N_2 is on the normal. N_1N_2 subtends angle θ at the mirror. If the point A of the scale was focused in the telescope with the mirror at M_1 and the point B with the mirror at M_2, then AB subtends angle 2θ at the mirror.]

tally on the stand. Place the telescope where your eye had been before you clamped the lamp. Direct the telescope towards the mirror and look for the image of the lamp. Move the lamp near the telescope keeping its image in the field of view until the lamp is close to the scale. Turn the lamp shade to screen the mirror. The illuminated scale may now be seen. Adjust for best view of the scale (in the telescope) and focus the scale. Measure the distance D between the mirror and the scale with a measuring tape.

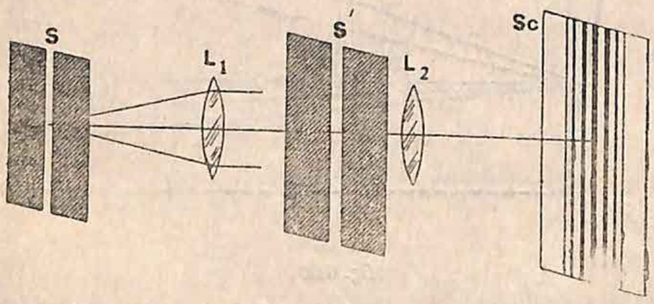
If the mirror turns about a vertical axis through a small angle θ (in radians), the scale reading in the distant telescope will change by d ($=AB$; Fig. 6.30) where

$$d=2D\theta \text{ whence } \theta=d/2D.$$

Note that the scale should be parallel to the mirror.

6-17. To determine of the width of a slit by measuring the diffraction fringes produced by it

Theory. Let a parallel beam of monochromatic light from an illuminated slit S fall normally on a second slit S', parallel to the first (Fig. 6.31). If the transmitted light is observed through a telescope *focused for infinity* and rotating about the second slit as axis, a number of diffraction fringes will be observed on either side of the central maximum. If θ_n (Fig. 6.32) be the angle between the direct beam and the nth *minimum* on either side, 'a' the width of the second slit and λ the wavelength of the monochromatic beam then



Fig, 6.31

$$n\lambda=a \sin \theta_n. \quad \cdots \quad (6\text{-}17.1)$$

As θ_n is very small, we may write $\sin \theta_n = \theta_n$

$$\therefore \; n\lambda = a\theta_n \quad \text{or} \quad a = n\lambda/\theta_n \qquad \cdots \qquad (6\text{-}17.2)$$

where θ_n is in radians. Knowing n and λ and measuring θ_n, 'a' the width of the slit may be determined.

As θ_n is very small and corresponds only to a few vernier divisions of the spectrometer, it is usually measured by a telescope and scale arrangement (see Sec. 6-16). A small plane mirror with its plane vertical is attached to the observing telescope and the reflected image of a horizontal scale placed at a distance is observed through a second telescope. If d be the linear shift of the scale division coincident with the cross-wires of the second telescope when the observing telescope is turned through an angle θ, then $\theta = d/2D$, where D is the distance of the scale from the mirror.

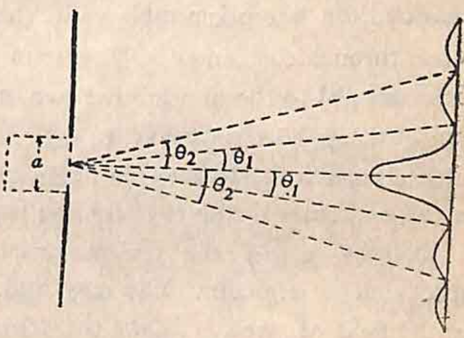


Fig. 6.32

The scale should be parallel to the mirror.

List of apparatus. As in Sec. 6-12. ; experimental slit mounted vertically on horizontal stand (a slit of width 0·1 – 0·2 mm is suitable) ; scale-and-telescope arrngement ; small mirror for mounting on telescope.

Instructions. The preliminary adjustments are threefold ; (a) adjustment of the spectrometer, (*b*) setting up of the telescope and scale arrangement for measurement of angle, and (*c*) setting up of the slit on the prism table.

(*a*) Make adjustments (1) to (5) of the spectrometer as stated in Sec. 6-12. Remove the prism and set the telescope for direct reading.

(*b*) Take a small plane mirror mounted vertically on a suitable horizontal base, and attach the base to the tube of the telescope with a little wax so that the mirror is vertical. In the manner described in Sec. 6-16 set up a scale and telescope at a distance of two metres or more from the mirror. The line joining the scale and the mirror should be perpendicular to both. Adjust so that a clear image of the scale is seen through the telescope. The lamp used to illuminate the scale should be screened off from the rest of the room.

(*c*) Place the stand carrying the slit whose width is to be measured on the prism table such that the central line of the slit passes through the centre of the prism table, and the plane of the slit is parallel to the line joining two of the levelling screws. Adjust the third screw, if necessary, to make the plane of the slit approximately vertical. Rotate the prism table until the plane of the slit is perpendicular to the rays coming from the collimator.

Narrow down the collimator slit and look at it through the spectrometer telescope. You may find indistinct diffraction fringes in the field of view. Make the fringes as distinct as possible by turning one of the two prism-table screws, the line joining which is parallel to the plane of the slit.

Now increase the width of the collimator slit to make the fringes as bright as possible without impairing their distinctness.

The maximum width of the collimator slit for this condition is $\lambda f/4a$, 'a' being the width of the second slit and f, the focal length of the collimator lens.

From the above condition it is evident that if the width of the slit to be measured be 0·1 mm and if the focal length of the collimator lens be 25 cm, then, for sodium light, the maximum width of the collimator slit should be about 0·37 mm. For a weak source, such as a bunsen burner illuminated with sodium salt, the width of the second slit should not exceed 0·5 mm. The maximum width of the collimator slit in such a case should be 0.074 mm for distinct diffraction fringes.

To get favourable experimental conditions where there will be several clear, bright fringes, a strong monochromatic source, such as a sodium lamp with a cylindrical condenser lens to focus the rays on the collimator slit, should be used. Set the cross-wires of the spectrometer telescope on successive *minima*, say from left to right. For each setting note the scale reading coincident with the cross-wires of the second telescope, and record the *order* (n value) of each minimum. Remember that the minimum nearest to the central bright band has the order one, the next one two, etc. Measure the distance of the scale from the mirror.

If time allows, take a second set of readings from right to left. Use the mean reading for the same order by twice the order number, you get the distance corresponding to θ_1. Note that it is not required to use the spectrometer scale.

Calculate a from the mean value of θ_1 so obtained, and verify your result using a travelling microscope.

Note. Method of recording, including that of experimental results, has been described at the end of the experiment below (Sec. 6-18), because the latter cannot be separated from the former.

6-18. To determine the width of a narrow obstacle separating two identical narrow slits by observing the diffraction and interference fringes they produce.

Theory. Let a parallel beam of monochromatic light from an illuminated slit S fall normally on a plane containing two identical slits of width a separated by a distance b, the slits being parallel

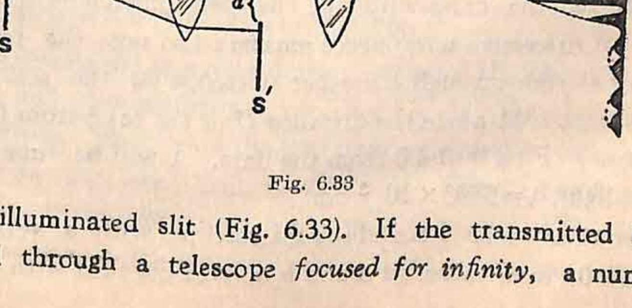


Fig. 6.33

to the illuminated slit (Fig. 6.33). If the transmitted light is observed through a telescope *focused for infinity*, a number of diffraction fringes similar to that due to a single slit will be observed. (These are represented by the dotted outline in Fig. 6.33). In addition, the diffraction maxima, including the central one, will be found to be crossed by interference fringes of equal width. (These are shown shaded in the figure). If θ be the angular distance between successive *diffraction minima*, and α the angular distance between successive *interference maxima* or *minima*, then

$\lambda = a \sin \theta$ for *diffraction* fringes, and

$\lambda = (a+b) \sin \alpha$ for *interference fringes.*

As θ and α are very small, we may write $\sin \theta = \theta$ and $\sin \alpha = \alpha$,

Then $\lambda = a\theta$ and $\lambda = (a+b)\alpha$.

Let d be the distance, on the scale (of the scale-telescope arrangement) corresponding to θ, and d' that due to α. If D is the scale-to-mirror distance, then $\theta = d/2D$ and $\alpha = d'/2D$. Thus finally

$$a = \frac{\lambda}{\theta} = \frac{2D}{d}\lambda \text{ and } a+b = \frac{\lambda}{\alpha} = \frac{2D}{d'}\lambda \qquad (6\text{-}18.1)$$

$$\therefore \quad b = 2D\lambda\left(\frac{1}{d'} - \frac{1}{d}\right) \quad \dots \quad \dots \qquad (6\text{-}18.2)$$

List of apparatus. As is the last experiment (Sec. 6·17) except that the single slit is replaced by the experimental double slit.

Instructions. All adjustment are exactly the same as in the case of the single slit experiment described in the last section (Sec. 6-17), except that the double slit replaces the single slit.

Measure the angular distance (θ) between successive *diffraction minima* on either side of the central maximum. In a similar manner, set the cross-wires of the spectrometer telescope on the centres of successive *interference maxima* and note the readings of the scale as seen through the other telescope (of the scale-telescope arrangement). Measure the distance D of the scale from the mirror (as before). Find a and b from the data. λ will be supplied. For sodium light, $\lambda = 5893 \times 10^{-8}$ cm.

If you have a good travelling microscope with a vernier constant of 0·01 mm, values of a and b may be checked with it.

Note. The slits may be 0·2 mm wide, separated by an obstacle 0·4 mm wide. At a scale distance at about 2 metres, diffraction minima and interference maxima will be measurable on the scale.

Experimental results :

Measurements on diffraction minima.

(The central maximum is taken as of zero order. Successive minima on two sides of it have order numbers 1, 2, 3, etc., and -1, -2, -3, etc.

The table below is drawn up assuming that altogether 4 can be seen on either side of the central maximum,

Order number n	Scale readings (x) on telescope scale		Mean δ_n of two readings of the same order	$2\delta_n = (\delta_n - \delta_{-n})$	$\delta_1 = d_1 = 2\delta_n/2n$
	Left to right	Right to left			
4	··· (c)	··· (c′)	$\cdots[\delta_4 = \frac{1}{2}(c+c')]$		
3					
2					
1					
−1					
−2					
−3					
−4			$\cdots(\delta_{-4})$		

Calculation.

Mean d_1 (for one fringe) $= \cdots$ cm

Distance D from scale to mirror on spectrometer $= \cdots$ cm

$\therefore$ Width (θ_1) of a single fringe $= d/2D = \cdots$ rad.

$2D/d_1 = \cdots$

Given wavelength $\lambda = \cdots \mathring{A} = \cdots \times 10^{-8}$ cm.

Result. Slit width $a = (2D/d_1)\,\lambda = \cdots$ cm.

For the *double slit* experiment you may use a similar table. But since there will be more fringes, you may not find time to take two sets of readings. Start from the extreme recognisable interference maximum on the left. Call it fringe 1. Then move fringe by fringe to the right as far as you can go. Take the difference in reading between 5 fringes, and then find the mean of all such differences. Divide it by 5. This corresponds to the width of a single interference fringe. Arrange the table as follows :

Fringe number	Scale reading	Difference δ for 5 fringes	Mean δ	Mean $\delta/5 = d'$	Mean d'
1	.. (d'_1)				
2					
3					
…					
6	.. (d'_6)				
7		.. $=(d'_6-d'_1)$			
8		…	.. (δ)	…(d'_1)	…
…		…			

Result : $b=2D\lambda\left(\frac{1}{d'_1}-\frac{1}{d_1}\right)=\cdots$cm

Note. You may come across one difficulty in locating an interference maximum—maxima which occur near a diffraction minimum. Such maxima have a very low intensity and may not be detected. In case of such difficulty, better use the interference fringes in only the central diffraction maxima. They will be fewer in number. Set the cross-wires on each maximum, take the scale reading and find the average distance between successive fringes.

The pattern of fringes you will get depends on the ratio of a to b If b is relatively large (that is, a is small), there will be more fringes of both kinds ; but the intensity will be low.

Method followed : (*single slit*)

1. The spectrometer was adjusted in the usual way and set for parallel rays.

2. The single slit was mounted on the prism table with its plane perpendicular to the beam from the collimator, and the length of the slit parallel to the collimator slit.

3. The fringes were made as bright as possible by adjusting the monochromatic source of light and the slit width of the collimator.

4. A small mirror was placed vertically near the objective end of the spectrometer telescope, and a scale-and-telescope arrange-

ment set at a distance of nearly ··· cm from the mirror to measure small angular deviations of the spectrometer telescope.

5. The *diffraction minima* were located, and readings taken of their position from one end to the other end. These were then repeated in the reverse order.

6. Data were recorded, calculations made and the slit width determined as shown.

Method followed : (*Double slit*)

1. As above.
2. For 'single slit' write 'double slit'.
3. As above.
4. As above.
5. The *diffraction minima* were located and readings taken of their position from one end to the other.
6. The *interference maxima* were located and readings taken of their position from one end to the other (or for the central diffraction maxima only, as the rest were very feeble).
7. Data were recorded, calculations made and results obtained as shown.

Oral questions (Single slit and Double slit).

1. What is the fundamental difference between diffraction and interference ?
2. Which of the patterns that you see here due to diffraction and which to interference ?
3. What causes the diffraction ? What causes the interference ?
4. What will be the effect of increasing *a* ? Increasing *b* ?
5. If you wanted bright fringes what should you do ?
6. What is the effect of widening the collimator slit ? Or narrowing it ?
7. What will be effect of holding the plane of the slit at an angle to the incident beam ?
8. How would you know that the plane of your slit is perpendicular to the incident beam ?
9. Why do we measure differences between diffraction *minima* but interference *maxima* ?

Answers.

1. When a beam of light passes through an aperture or past the edge of an opaque obstacle and is allowed to fall upon a screen, patterns of light and dark bands (with monochromatic light) or coloured bands (with white light) are observed near the edges of the beam, and extend into the geometrical shadow. The phenomenon is known as diffraction and is common to all wave motions.

Interference is the effect that takes place when waves from *coherent* sources are superposed. (Coherent sources are sources of waves that vibrate in the same phase.)

2. The wide pattern of maxima and minima seen in the spectrometer telescope is due to diffraction. The narrow pattern of maxima and minima occuring within a bright diffiraction band is due to interference.

3. The slit causes the diffraction. Interference is caused by the two slits acting as coherent sources.

4. Diffraction bands will be narrower. Interference bands will be narrower.

5. Use a strongly illuminated slit with the light coming along the axis of the collimator.

6. Widening will blur the pattern. Narrowing will reduce the intensity of the pattern.

7. The pattern will be shifted to one side of the central line of the spectrometer. (The side towards which the plane of the slit has been tilted.) The intensity of the remote fringes will be lower than that of those nearer the central line.

8. I shall first mark the position of the direct beam. If the central maximum of the diffraction pattern falls on this line, the plane of the slit is normal to the beam.

9, Diffraction minima occur when $a \sin \theta = n\lambda$. where n is an integer. Diffraction maxima do not satisfy such in tegral relations.

Interference maxima satisfy integral relations of the same kind [$(a+b) \sin \alpha_n = n\lambda$].

6-19. To determine the radius of curvature of the convex surface of a lens by means of Newton's rings.

Description of apparatus. The apparatus commonly used for this experiment is as shown in Fig. 6 34. A convex lens L, the radius of curvature of the lower surface of which is to be determined, is placed on an optically worked plane glass plate P. A bunsen flame illuminated with sodium salt is placed in the focal plane of another lens L' fitted in the circular aperture of a screen. A horizontal beam of rays from the lens L' falls on the surface of another glass plate P′ inclind to the vertical at an angle of 45°. The rays after reflection fall on the combination of the lens L and the glass plate P. A travelling microscope M, directed vertically downwards, magnifies the system of rings which forms practically on the glass plate P. The screen prevents light from the source from reaching the observer's eye.

Theory. When a monochromatic beam of light coming from an *extended source* is incident on a combination of L and P as shown in Fig. 6.34, a part of it is reflected from the lower surface of the lens and a part, after refraction through the film between L and P, is reflected back from the surface of the plate P. These two parts are in a condition to interfere and give rise to a system of alternate dark and bright rings with O, the point of contact (between L and P), as centre.

If the angle of incidence of the rays which fall on P is θ, and μ is the refractive index of the film between L and P, then the diameter D_n of the nth dark or bright ring is given by

$$D^2_n/4 = n\lambda R/\mu \cos\theta \quad \text{(for dark rings)}$$

$$D^2_n/4 = \frac{2n+1}{2} \times \frac{\lambda R}{\mu \cos\theta} \quad \text{(for bright rings)}$$

where λ is the wavelength of the light used and R is the radius of curvature of the lower surface of the lens L.

For normal incidence ($\theta = 0$), as in the arrangement shown in Fig. 6.34, and with $\mu = 1$, *i.e.*, with an air film between L and P, we have

$$D^2_n = 4n\lambda R \quad \text{(for dark rings)}$$

and $D^2_n = 2(2n+1)\,\lambda R$ (for bright rings)

Knowing λ and measuring the diameter of the nth dark or bright ring, R, the radius of curvature of the convex surface of the lens in contact with the plate P, may be determined.

But it is generally found that due to deformation of the lens surface near the point of contact, a few rings round the central dark spot are not circular. Further, due to presence of dust particles the central fringe may not be dark. In order to eliminate

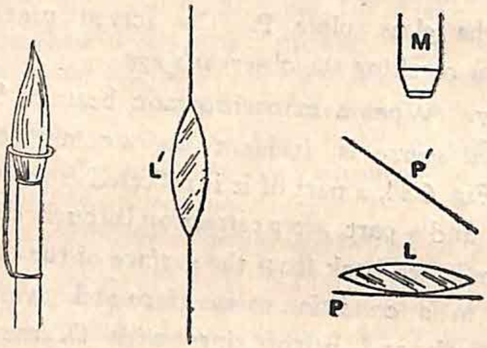


Fig. 6.34

difficulties arising out of these factors, the following procedure may be adopted for the detemination of R.

If D_{m+n} and D_n be the diameters of the $(m+n)$th and nth dark or bright rings, then

$D^2_{m+n} - D^2_n = 4m\lambda R$ (for the dark or bright rings).

The above relation indicates that R may be determined even without knowing the exact ring number $(m+n)$ or n. Thus by mesuring the diameters of any two dark or bright rings by means of a microscope and counting the number of dark or bright rings lying between them, R may be determined.

List of apparatus. Newton's ring apparatus containing lens L and plate P ; broad sodium flame placed about the focal plane of lens L′, plane glass plate P′ ; travelling microscope M.

Instructions. Arrange your apparatus as shown in Fig. 6.34. Level the microscope so that the scale along which it slides is horizontal and the axis of the microscope is vertical. Focus the eyepiece on the cross-wires. Find the vernier constant or the least count of the micrometer screw of the microscope. Carefully clean the sufaces of the glass plate P and the lens L by means of cotton moistened with benzene or alcohol. Place the glass plate P as shown in the figure and focus the microscope for a small speck of dust particle or any mark on its upper surface. Now place the lens L on it such that the centre of the lens L is vertically below the microscope objective. Adjust the position of the sodium ring on the bunsen flame so that an extended bright surface of the illuminated flame is in front of the lens L′ at a distance approximately equal to its focal length. If you now look into the microscope, probably you will see alternate dark and bright rings. Adjust the glass plate P′ by rotating it about a horizontal axis till a large number of evenly illuminated bright and dark rings appear on both sides of the central ring. Adjust the position of the lens L′ with respect to the flame so that a maximum number of rings are visible through the microscope.

After completing these preliminary adjustments, focus the microscope on the centre of the ring system by sliding the microscope as also by carefully moving the combination L and P, if necessary. Focus the microscope to view the rings as distinctly as posible and set one of the cross-wires perpendicular to the direction along which the microscope slides. Displace the microscope to the left counting the number of bright rings passed and set it on the *remotest distinct bright ring* so that the cross-wire perpendicular to the line of traverse of the microscope passes through the middle of the bright ring and is tangential to it. Take the reading of the microscope. Slide back the microscope and set it similarly on the next bright ring. In this way take readings for three or more consecutive bright rings. Next pass off a number of intermediate rings and again take readings for three or more consecutive rings near the centre, of course *avoiding* the few deformed rings which form round the centre. Next slide the microscope to the right and again take readings setting the cross-wire on the same rings as before. During experiment take care not to disturb the combination in any way. In the case of a microscope provided with a micrometer screw arrangement, take special care to avoid backlash error.

From the readings taken determine the diameters of the rings observed. Repeat the experiment by sliding the microscope back from right to left and again from left to right taking readings for the same rings as before. If time permits repeat the whole experiment by rotating the lens combination through a right angle.

Tabulate you data as follows.

Experimental results :

Vernier constant or constant of the micrometer screw :

[Record details as in other experiments]

Measurement of the diameters of the rings :

[Specific values of ring number are given only for illustration.]

Ring No.		Reading of the microscope (in cm)						Diam D cm	Mean D cm
		Left			Right				
		Main Scale	Vernier or C.S.	Total	Main Scale	Vernier or C.S.	Total		
26th	(*i*)	....	....	....	....	....	....		
	(*ii*)	....	....	....	....	....	....	....	
	(*iii*)	....	....	....	....	....	....	....	....
25th								....	
etc,									
6th	(*i*)	....	....	....	....	....			
	(*ii*)	....	....	....	....	....	....	....	
	(*iii*)	....	....	....	....	....	....	....	....
5th							....	....	
etc.									

Ring No.	D	D^2	$D^2{}_{m+n}-D^2{}_n$	Mean $D^2{}_{m+n}-D^2{}_n$
26 th	......	$\cdots(D^2+n)$	......	
25th	......	...	......	
24th	......	...	......	
6th	......	$\cdots(D^2{}_n)$		......
5th	......	...		
4th	......	...		

Mean wavelength of sodium light $(\lambda)=5893$ Å

$=5893\times10^{-8}$ cm and $m=\cdots$(here 20 as tabulated)

$$\therefore \quad R=\frac{D^2{}_{m+n}-D_n{}^2}{4m\,\lambda}=\cdots\cdots\text{cm.}$$

Result : The radius of curvature of the lower surface of the given lens$=\cdots$cm.

Method followed : (*A* brief statement.)

1. A long focus lens was laid on a clean, optically flat glass plate. Light from a broad, monochromatic source was allowed to fall on the combination, normal to the plate.

2. A long focus travelling microscope is then focused vertically on the air gap between the lens and the plate near their point of contact. A number of concentric, circular dark and bright-rings are seen in the field of view of the microscope. These are Newton's rings. The rings near the centre may be slightly distorted due to distortion of the glass surfaces near their point of contact. The central ring is generally dark.

3. Diameters of a number of bright rings are then measured with the mircoscope. From the data so obtained the radius of curvature of the lower surface of the lens was measured in the way shown above.

Oral questions.

1. What do you understand by intereference of light ?
2. How does interference take place in the formation of Néwton's rings ?
3. Can light from two independent sources interfere ?
4. Where are the rings formed in this case ?
5. Where are the interfering sources in this case ?
6. Why is an extended source necessary in this case ? What would happen if you had a point source or a slit instead of the extended source ?
7. What would happen if you use white light in place of sodium light ?

Answers.

1. See answer to Q. 1 of Sec. C-18.

2. In this case, a ray of light reflected from the glass plate falls practically normally on the air gap between the long focus lens and the plate below it. A part of the ray is reflected from the upper side of the air gap, and another from the lower side. When these two are combined by the microscope (or the eye), there may be no illumination at the point if the two fractions of the ray are in opposite phases. Whether the two fractions will be in opposite phases depends on the extra optical distance traversed by one part. The rings are circular because places of equal thickness are circular. When the two parts are in phase, the point is bright.

The interfering rays are the two parts of the same ray. Each point of the pattern is formed by different rays. So the source has to be wide. The two parts are coherent as they are derived from the same ray.

3. No, because there is no phase relation between light from different sources.
4. The rings are formed on the underside of the lens.
5. See answer to Q. 2
6. See answer to Q. 2. Only a small part of the entire pattern could be seen.
7. The diameter of a ring depend on the colour of the light. For light of different colours a ring will have different diameters. Near the centre there will be a few coloured circles. But a little beyond, there will be so much superposition that no distinct circle of one colour can be made out.

6.20. Rotation of the plane of polarization : Polarimeter.

A ray of light may be considered to consist of transverse waves whose oscillations occur at right angles to the directions of travel. These directions are distributed over an infinite number of planes containing the ray. The light is said to be **linearly polarized** (or **plane polarized**) when the oscillations are confined to one plane.

Linearly polarized light may be produced by passing light through a suitably cut prism of calcite, called a **nicol.** When a monochromatic source of light is examined through two such prism, the intensity of the transmitted light varies as the first prism (the one nearer to the source) is rotated. This prism is called the **polarizer,** the other the **analyser** (the one nearer the eye). The prisms are said to be *crossed* when the intensity of the transmitted light falls to a minimum. As the analyser is turned through 360°, the intensity passes through two maxima and two minima. At minima, we get practically complete darkness. Direction of vibration of light passing through a nicol is *parallel to the short diagonal of the end section.*

If a vessel containing a solution of certain crystalline substances (called *optically active substances*) be inserted between the analyser and the polarizer when the intensity of the light is a minimun, the intensity increases. The intensity can again be reduced to a minimum by rotating any one of the prisms, say, the analyser.

This shows that the effect of the solution has been to rotate the plane of polarization. This phenomenon, called **optical activity**, is shown by some solids and liquids (sugar solution among them).

The optical activity of a substance is defined by its *specific rotation.* For solutions, the *specific rotation* is given by

$$\frac{\text{rotation per decimetre of optical path through solution}}{\text{grams of optically active substance per cm}^3\text{ of solution}}$$

Specific rotation is not a constant. It depends upon the wavelength of light used and the temperature of the solution.

To measure the rotation of the plane of polarization, a special piece of apparatus, called a *polarimeter,* is used. Its essential parts are a polariser, an analyser, and a tube for holding the solution. Besides, there is a circular scale with verniers for measuring the rotation and one or two eyepieces for taking readings.

Unfortunately, the analyser can be turned through an appreciable angle without any change in the minimum becoming detectable. This lack of sensitivity can be overcome by using special devices. Of these, the one to be used with *white light* is the *biquartz.*

6-20 1. **Biquartz.** It consists of two equally thick semicircular plates of quartz which form a complete circle. One is of right-handed quartz (that is, of quartz crystal rotating the plane of polarization clockwise). The other is of left-handed quartz*, both being cut perpendicular to the optic axis.

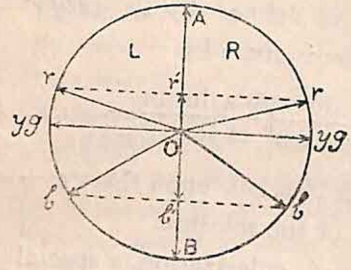
When a plane polarized beam of light passes through the plates, one of them rotates the plane of polarization clockwise and the other anti-clockwise.

The amount of rotation depends on the thickness of the plates and the wavelength. For a thickness of 3.75 mm the rotation is 90° for yellow-green light of wave-length about 5600 Å.

---

*Quartz crystals occur in nature in the two varities. One produces right-handed rotation, and the other produces equal left-handed rotation of the plane of polarization for the same thickness, wavelength and temperature.

Suppose the vibration in the light incident on the biquartz is parallel to AB (Fig. 6.35). (This is parallel to the short diagonal of the palarizing nicol). In each half the yellow green light would be rotated through 90° relative to AB. Red will be less deviated, but blue more, in both halves. If the analyser is set with its short diagonal parallel to AB, yellow-green light will be missing from both halves, while components of other colours will be transmitted in equal proportions in both halves. The colour will appear to be a greyish violet and is known as the tint of passage.



Flg 6.35

If the analyser is turned slightly from this position, one half of the field will appear pink, and the other a dark blue, as one half will transmit more of red and the other, more of blue. It is easy to detect an inequality of colour in the two halves of the field. Hence the setting of the analyser on the tint of passage can be fairly accurate. The experiment consists in so setting the analyser before and after insertion of the specimen and measuring the rotation necessary to get the tint of passge.

6-20.2. Description of the biquartz polarimeter

The tube (T., Fig. 6.36) which holds the solution has carefully worked end-pieces. The ends are held in position by metal caps screwed against them. It is necessary to have rubber washers between the glass ends and the tube to avoid strain when screwing

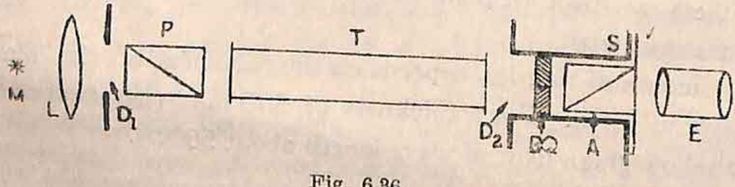


Fig. 6.36

up, for a strained end will produce rotation. The tube may have a metal cover to guard against temperature change. A lens L focuses the source M (a white pearl bulb is convenient) on the diaphragm D_2 so as to throw maximum light on the field of view. A long focus microscope is focused on the line of sepatarion of the two parts of the field. D_1 and D_2 are diaphragms to limit the beam. P and A are respectively the polarizer and the analyser. The analyser is fitted with a vernier which moves over a fixed circular scale S. (There may be two verniers 180° apart.) The biquartz, analyser and microscope turn together about the common axis of the polarimeter. The line of separation of the biquartz and the short diagonal of the analyser are parallel.

Two positions of analyser for tint of passage.

In Fig. 6.37, ABCD is the end section of the analyser and BD its short diagonal. Let the plane of vibration of the light reaching the analyser be parallel to EF. Then if the nicol be turned through the angle BOE, we shall get the tint of passage. We shall also get it if we turn the analyser through angle BOE in the opposite direction. The sum of these two angles is 180°. Generally, we work with the smaller angle.

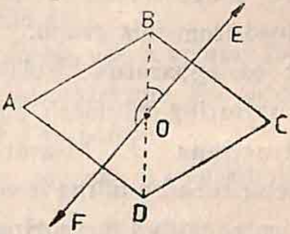


Fig. 6.37

6-21. To calibrate a polarimeter and hence determine the concentration of sugar solution

(*Mother solution to be supplied*)

Theory. The specific rotation α of an optically active solution for wavelength λ and temperature t°C is given by

$$\alpha = \frac{10\,\theta}{lm} \qquad (6\text{-}21.1)$$

where θ=angle of rotation of the plane of polarization in degrees,

l=length of the light path through the solution in cm, and

m=mass of the optically active substance in grams per cm^3 of the solution at t°C. ($m\times 100$ is the number of grams per 100 cm^3 of the solution. This ($100m$) is called the concentration c of the solution by volume.)

We may therefore write.

$$\alpha=\frac{10\ \theta}{l(c/100)}=\frac{1000\ \theta}{lc} \quad \text{or} \quad \theta=\frac{\alpha l}{1000}c. \qquad (6\text{-}21.2)$$

If a biquartz is used with white light to give the tint of passage, the effective value of λ is about 5600 Å (a constant). If we also hold l and the temperature const, the last equation (Eq. 6-21.2) shows that θ is proportional to the concentration c of the solution.

A graph of θ against c will be a straight line. If a solution of unknown concentration c' produces rotation θ', then c' can be determined from this graph.

List of apparatus. Polarimeter ; pearl bulb ; lens ; metre scale ; measuring cylinder ; burette ; distilled water ; beaker.

Instructions. 1. Measure the internal volume v of the polarimeter tube by filling it with water and measuring the volume of this water with a measuring cylinder (or burette).

2. Rinse the tube well with distilled water and then fill it with distilled water at the room temperature. See that no air bubbles stick to the tube. Place it in position.

3. Align the source along the axis of the tube and focus it on the aperture of the analysing nicol.

4. Set the analyser for tint of passage and read the vernier. Take at least three readings, each time after slightly disturbing the earlier setting of the nicol. The mean reading (θ_0) corresponds to $c=0$, and is taken as the zero position of the analyser.

5. Take out the tube. Throw away the distilled water. Rinse the tube with the mother solution supplied. Fill the tube

with the mother solution (which should be at the room-temperature). Place the tube in position. Be careful not to allow any air bubble to form inside the tube.

6. Turn the analyser and set it for the tint of passage (sameness of colour in both halves of the field). At an angle inclined at 180° to this position, the analyser will again give you sameness of colour in both halves.

7. Of these two positions of sameness of colour in both halves, use the position which makes the smaller angle with the zero position of the analyser.

Read this smaller angle thrice, each time disturbing the previous setting. Take the mean value. If this is θ_I, the rotation for the mother solution is $(\theta_I - \theta_0) = \theta_1$.

8. Dilute the mother solution from the tube by adding an equal volume v of distilled water to it. This reduces the original concentration c to $\frac{1}{2}c$.

Rinse the tube with this solution and then fill the tube (with the diluted solution). Note the corresponding rotation $\theta_2 (= \theta_{II} - \theta_0)$ as before. This is for a concentration $\frac{1}{2}c$.

9. If you had enough *mother solution*, add a volume $2v$ of distilled water to it to give it a concentration $\frac{1}{3}c$. *Measure* the corresponding rotation $\theta_3 = (\theta_{III} - \theta_0)$ as before

10. If time permits, you may prepare a solution of concentration $\frac{1}{4}c$ and find θ_4.

11. Plot the θ values against the corresponding concentrations. You should get a straight line passing through the origin. This is the required *calibration curve*

12. **Now** using the solution of unknown concentration c', measure the corresponding rotation θ'. From the calibration curve find c'. (If the concentration of the mother solution is given *numerically*, use that value for c.)

Experimental results.

Inner volume of the tube = (*i*)··· cm^3 ; (*ii*) ··· cm^3, (*iii*) ··· cm^3,

Mean = ··· cm^3.

Length of the tube = ··· cm

Vernier constant of the circular scale.

[Record as in 'Experimental result's of Section 6-13.]

Room-temperature : (*i*) Before experiment = ··· °C.
(*ii*) After experiment = ··· °C.

Concentration of solution	Position of analyser		Total	Rotation of plane of polarization
	Main scale	vernier		
O (Distilled water)	(*i*) (*ii*) (*iii*) Mean		···(θ_0)	0
c Mother soln.	(*i*) (*ii*) (*iii* Mean		···(θ_I)	($\theta_I - \theta_0$ $= \theta_1$)
$\frac{1}{2}c$	(*i*) (*ii*) (*iii*) Mean		···(θ_{II})	($\theta_{II} - \theta_0$ $= \theta_2$)
$\frac{1}{3}c$	(*i*) (*ii*) (*iii*) Mean		···(θ_{III})	($\theta_{III} - \theta_0$ $= \theta_3$)
and so				
c' (Unknown concentration)	(*i*) (*ii*) (*iii*) Mean		···(θ_u)	($\theta_u - \theta_0$ $= (\theta')$

Calculation. A graph is drawn plotting rotations (in the last column) against the known concentrations (in the first column). This is the *calibration curve*. It is a straight line passing through the origin.

The value c' as obtained from this graph corresponding to the value θ' of rotation gives the unknown value of concentration of the solution supplied.

Result. The concentration of the solution of unknown value = ···% by volume.

[**Note.** Note that you will be given two solutions—(*i*) the mother solution of known concentration (c), and (*ii*) the other of unknown concentration which is to be determined from the graph. Don't confuse the two.]

Method followed. (A brief statement)

1. The length and internal volume of the polarimeter tube were measured. It was filled with distilled water and placed in position.

2. The white source of light was placed along the axis of the tube. Rays from it were concentrated by a lens on entrance aperture of the analyser system, so as to give the field of view maximum light.

3. Vernier constant of the circular scale was determined.

4. Analyser was set to get the tint of passage. This position (θ_0) marks the zero position for measuring rotations.

5. The tube was next rinsed and filled with the mother solution. The two positions of the analyser for which the two halves of the field of view had the same colour were found. The analyser was then set in the position in which the angle of rotation of the analyser was smaller. This position θ_{I}) was carefully read. The rotation θ_1 for the mother solution (of concentration c) was $\theta_1 = \theta_{\mathrm{I}} - \theta_0$.

6. The mother solution was diluted to concentrations $\frac{1}{2}c$, $\frac{1}{3}c$ etc. by addition of the proper quantitity of distilled water. For each new concentration, the rotation was determined in the same way as for the mother solution.

7. The rotation—concentration graph was drawn from the data obtained. It was a straight line passing through the origin.

8. The rotation θ' corresponding to the given solution of unknown concentration was then measured. From the graph, the concentration c' corresponding to it was determined.

Precautions. (*i*) The tube was rinsed several times with the solution with which it was to be filled.

(*ii*) Care was taken to see that no air bubble remained inside the tube.

(*iii*) The mother solution and the distilled water were left at the room-temperature long enough for them to acquire that temperature. The room-temperature was read before and after the experiment.

[**Remark**. If the tubelenth of the polarimeter is about 20 cm and you use a 25% sucrose solution, the rotation will be about 33° in the clockwise direction.]

Oral questions.

1. State the meanings of the terms, *polorizer*, *analyser*, *optical activity* and *specific rotation*.

2. What is a nicol prism ? How is it constructed ? How does it give a plane polarized beam ? What is meant by nicols being crossed ? What is the direction of vibration of light in the transmitted beam ?

3. What is a *biquartz* ? How does it act ? With what kind of light source is it used ? Can it be used with a monochromatic source of light ?

4. What are meant by right-handed and left-handed rotation of the plane of polarization.

Is the rotation produced by sugar solution right-handed or left-handed ?

5. Has your solvent any optical activity ? What would be the effect if it had some ?

6. Since rotation depends on wavelength, what is the wavelength for which you have determined θ ?

Answers.

1. See Sec, 6-20,

2. Consult your text-book for construction and action.

The direction of vibration in the transmitted beam is parallel to the short diagonal of the end section of a nicol.

When one nicol is so set that it fully cuts out the beam of light from another nicol, the two are said to be *crossed*. Their short diagonals are than perpendicular to each other.

3. See Sec. 6-20.1, The biquartz is specially designed for use with white light. It is unsuitable for use with monochromatic light.

4. An optically active substance which rotates the plane of polarization *clockwise* is called *right-handed*. One which rotates the plane *anticlokwise* is called *left-handed*.

In sugar (sucrose) solution, the rotation is right-handed. Invert sugar produces left-handed rotation.

5. Pure water is optically inactive. If the solvent were optically active, rotation due to it would be algebraically added to that of the solute.

6. A biquartz balances the two halves of the field for the yellow-green region of the spectrum. The wavelength of this region may be taken approximately as 5600Å.

CHAPTER 7

MAGNETISM

7-1 Magnetometers

Deflection magnetometer This instrument (Fig. 7.1) has a small compass needle provided with a long aluminium pointer fixed symmetrically to it in its middle and at right angles to its length. The needle with the pointer is either pivoted or suspended by means of an unspun silk fiber at the centre of a circular scale graduated in degrees. The circular scale is divided into four quadrants and each of them reads from 0°—90° as shown in the figure. The needle with the pointer is enclosed within a glass cover to protect it from draught. A circular strip of plane mirror is attached to the base of the scale which helps to take readings of the pointer avoiding parallax.

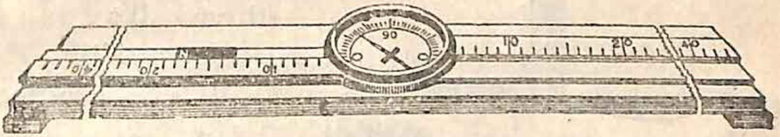


Fig.7.1

The enclosed needle is placed at the centre of a long rectangular wooden base such that the 0°—0° line of the circular scale is exactly parallel to the two metre scales fixed on either side of the compass needle along the length of the wooden base. The zero of both the metre scales lie on the 90°—90° line of the compass needle. The metre scales are so fixed on the board that when a small magnet (as ordinarily used in the laboratory) is placed alongside any one of them, the axis of the magnet practically passes through the axis of rotation of the compass needle.

Vibration magnetometer. It consists of a magnet M placed on a light brass stirrup and is suspended by an unspun silk fibre from a torsion head H as shown in Fig. 7.2. The combination hangs within a box provided with glass walls. A mirror with a central line LL marked on it is placed on the floor of the box.

There are two slits at the top cut parallel to LL. The line at the slits help in finding the time of transit of the magnet when it oscillates. In order to use the instrument, the magnet is removed from the stirrup and the box is rotated such that LL lies in the magnetic meridian. The torsion head H is next adjusted such that when the stirrup is in equilibrium, its horizontal axis (and hence also the axis of the magnet when it is placed on the stirrup) lies in the magetic meridian.

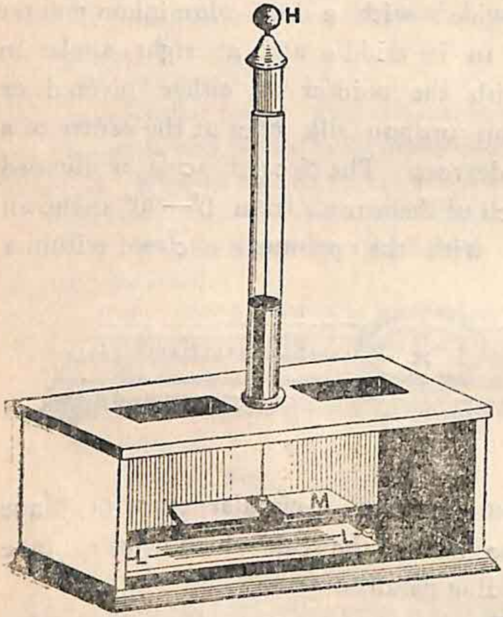


Fig. 7.2

When adjusting a deflection or a vibration magnetometer, all magnets and magnetic materials should be removed from the neighbourhood of the instrument.

7-2 To determine the horizontal component of the earth's magnetic field and magnetic moment of a bar magnet.

Theory. When a bar magnet is brought near a magnetic needle so that the needle is in the *end-on position* of the magnet (Fig. 7.3) and the earth's magnetic field is at right angles to the axis of the bar magnet, the deflection θ of the magnetic needle from the magnetic meridian is given by

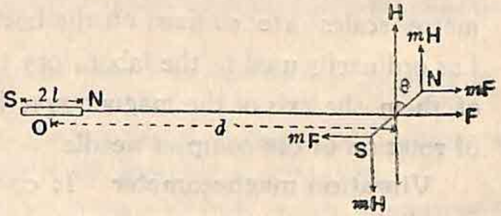


Fig. 7.3

$$\frac{M}{H}=\frac{(d^2-l^2)^2}{2d}\tan\theta \qquad (7\text{-}2.1)$$

where M is the magnetic moment of the bar magnet, H the horizontal component of the earth's magnetic field, $2l$ the *magnetic length* of the bar magnet and d the distance of the needle from the centre of the magnet.

If the same bar magnet is allowed to oscillate at the same place in a vibration magnetometer in the earth's magnetic field with its axis horizontal, then, neglectiing the effects of the moment of inertia of the stirrup and the torsional couple exerted by the suspension fibre (which are small quantities), the time period of oscillation T of the bar magnet is given by

$$T=2\pi\sqrt{I/MH} \tag{7-2.2}$$

where I is the moment of inertia of the bar magnet about the axis of suspension.

If the magnet is a rectangular one and the axis of suspension is normal to the broad face of the magnet and passes through its centre of gravity, then

$$I=m\frac{l'^2+b'^2}{12} \tag{7-2.3}$$

where l', b' and m are the geometrical length, the breadth and the mass of the magnet respectively.

(*i*) **To determine the horizontal component of the earth's magnetic field (H) :**

From Eq.s 7-2.1 and 7-2.2, we have

$$H=\sqrt{\frac{MH}{M/H}}=\sqrt{\frac{4\pi^2 I}{T^2}\times\frac{2d}{(d^2-l^2)^2\tan\theta}} \tag{7-2.4}$$

As all the quantities on the right hand side of this equation may be measured, H may be computed.

(*ii*) **To determine the magnetic moment of a bar magnet (M) :**

From Eq. 7-2.2 we have

$$MH=4\pi^2 I/T^2 \tag{7-3.1}$$

Multiplying this equation by (7-2.1), we get

$$MH \times \frac{M}{H} = \frac{4\pi^2 I}{T^2} \times \frac{(d^2 - l^2)^2}{2d} \tan\theta$$

$$\therefore \quad M = \frac{2\pi(d^2 - l^2)}{T} \times \sqrt{\frac{I \tan\theta}{2d}} \qquad (7\text{-}3.2)$$

[**Unit.** Since magnetic moment is defined as the mechanical moment of the couple required to hold the magnet at right angles to a magnetic field of unit strength, the unit in which magnetic moment may be expressed is one *dyne-cm per oersted.*]

List of apparatus. Deflection magnetometer ; vibratio magnetometer ; bar magnet ; balance; weight box ; long magneti needle to determine magetic meridian ; slide-callipers.

Instructions. 1. Weigh the bar magnet and measure it geometrical length and breadth by means of a slide callipers Calculate its moment of inertia *I* from the equation 7-2.3

2. Determine the magnetic length 2*l*, which is about 0·85 time the geometrical length. (This factor is not a constant but depend on the ratio of the geometrical length to the breadth of the magne For small magnets of length about 6 or 7 cm and breadth about cm. as are ordinarily used in the laboratory, the value of the facto may be taken as 0·85.)

3. Remove all magnets and magnetic materials from th neighbourhood of the deflection magnetometer.

Adjust its position so that the pointer reads 0°, 0°. Then for properly constructed magnetometer, the magnetic meridian is a right angles to its length, that is the magnetometer scale poin magnetic east-and-west.

4. Place the bar magnet alongside one of the metre scales, say east of the compass needle with its north pole facing the needle Adjust its position so that a fairly large deflection, about 45° o the needle is produced.

Turn the magnet upside down in the same position and observ the deflections of the pointer.

Keeping the magnet at the same distance, reverse the pole facing the needle and observe deflections as before. Again turn it upside down and read the deflections.

5. Determine *d*, the distance of the needle from the centre of the magnet. It is the mean of the readings of the ends of the bar magnet.

6. Repeat observation 4 above placing the magnet west of the needle, but at the same distance as before.

Find the mean deflection θ, the mean of the observed sixteen readings.

7. Repeat your observations for other two deflections of the needle, one greater than 45° and other less than 45°.

8. Use the long magnetic needle to mark the magnetic north-and-south direction on the working table. Adjust the position of the vibration magnetometer such that the line *LL* on its floor (Fig. 7.2) is in the magnetic meridian.

Rotate the torsion head till the axis of the stirrup, when in equilibrium, is parallel to the line *LL*.

9. Place the bar magnet on the stirrup with its north pole pointing north and allow it to oscillate with as small an amplitude as is convenient. Measure the time for 30 oscillations, at least three times, observing through a slit at the top the transists of the magnet across the *LL*.

Hence find the mean time period and calculate *H* from Eq. 7-2.4.

Experimental results :

Mass of the bar magnet $(m) = \cdots + \cdots + \cdots + \cdots$ (details of weights)

$= \cdots\cdots\cdots$ g.

Length (l') *and breadth* (b') *of the magnet (in cm)* :

1 Small seale div. $= \cdots mm$

$\cdots V.\ D = \cdots\ S.\ D$

$\therefore\ V.\,C = \cdots mm = \cdots cm.$

zero error $= \cdots mm = \cdots$ cm (to be added/Subtracted)

Dimension	No. of obs.	M. S. reading cm.	Vernier reading	Value of vernier reading cm	Total cm	Mean cm	Corrected Mean cm
Length (l')							
Breadth (b')							

$$\therefore\ I = m \times \frac{l'^2 + b'^2}{12} = \cdots\cdots \text{g. cm}^2.$$

$2l = 0{\cdot}85\ l' = \ \cdots$ cm ; $\therefore\ l = \cdots\cdots$ cm.

Deflections :

No. of obs.		Magnet east				Magnet west				Mean θ
		Pole facing needle				Pole facing needle				
		N		S		N		S		
		End I	End II	End I	End II	End I	End II	End I	End II	
1.	Face up									
	Face down									
2. etc										

Periodic time :

Time for 30 oscillations :

(i)……s ; (ii)……s ; (iii)……s. Mean=…s.

∴ Time period $T=$……s.

(1) $H=\frac{2\pi}{T(d^2-l^2)}\times\sqrt{\frac{2Id}{\tan\theta}}=$……oersted.

(2) $M=\frac{2\pi(d^2-l^2)}{T}\sqrt{\frac{I\tan\theta}{2d}}=$dyn-cm/oersted.

Method followed.

1. The moment of inertia of the given bar magnet was calculated by measuring its mass, length and breadth.

2. Magnetic length of the magnet was taken as 0·85 times the geometrical length.

3. The deflection magnetometer was placed with its scale pointing magnetic east-and-west. The bar magnet was placed by the side of the scale at a distance of…cm from the magnetic needle, so as to produce a deflection of about 45°.

4. Readings of both ends of the pointer were taken with (*a*) the magnet turned upside down, and (*b*) north and south poles interchanged.

5. Readings as in (4) were then taken with the magnet placed at the same distance from the needle, but on the other side.

6. The observations were repeated for other two deflctions of the needle.

7. The vibration galvanometer was then set with its median line along the magnetic meridian, and the axis of the stirrup parallel to it.

8. The bar magnet was placed on the stirrup and its periodic time determined for oscillations of small amplitude.

9. From the data so secured, the result was calculated.

Precautions.

(i) The deflection should be large so that the error may be small. 45° is best ; but d should not be too small.

(ii) To minimise the effect of friction at the pivot, lightly tap the magnetometer box before reading the deflection.

(iii) There must be no other magnet or magnetic material close to the magnetometers.

Note. 1. To get a good result in this experiment, a strong bar magnet should be used. Then both d and θ may be kept large. This will reduce the error in H. Further, d being large, an error in evaluating the magnetic length l will not appreciably affect the final result.

2. The suspension of the vibration galvanometer *must be torsionless*. It should be of unspun silk. *Use of a wire of any kind will spoil the experiment.*

Oral questions

1. What do you mean by 'the horizontal intensity of the earth's magnetic field ? Describe the nature of the earth's field ? What is meant by 'the magnetic elements of the earth's field' ? Which of them gives the actual direction of the field ?

2. Define the magnetic moment of a magnet, What is magnetic length ? Can you find it experimentally ? Will the ratio of the magnetic length to the geometrical length be the same for a long thin magnet and a short, broad magnet ?

3. Will the presence of another magnet on your working table affect your result ? Is there any harm if the magnetometers are placed at different places ?

4. What do you understand by 'end-on position and broad-side-on position' ? What are Gauss' tangent A and tangent B positions ? Why do you work in one of these positions ?

Answers. 1. See answer to Q. 1. of Sec. 7-5. The earth's field is roughly like that produced by a very strong magnet placed in the centre of the earth, with its axis inclined at about 12° to the earth's north-south axis. The north pole of this imaginary magnet points towards the south.

The 'dip' gives the actual direction of the field.

2. See after 'Instructions' in Sec. 7-3.

Magnetic length of a magnet is the distance between its poles. It can be found experimentally by locating the poles by tracing lines of force. Lines of force come out from the north pole and terminate on the south pole. Magnetic length depends on the size and shape of the magnet. The ratio of the two lengths will be bigger for longer magnets.

3. The field of the other magnet will modify H and vitiate the result. If the places have the same H, there will be no harm.

4. When the needle of deflection magnetometer lies on the axis of the deflecting magnet, the axial field of the magnet being perpendicular to the earth's horizontal field, the magnet is said to be in the 'end on' position. The magnet and the magnetometer are said to be in the 'tangent A position of Gauss'.

When the needle of a deflection galvanometer lies on the *equatorial plane* of the deflecting magnet, the equatorial field of the latter being perpendicular to the earth's horizontal field the magnet is said to be in the 'broad-side-on position'. Both the magnetometer and the magnet are said to be in the 'tangent B position of Gauss'.

For the tangent law to hold, the deflecting field and the restoring field acting on a magnetic needle must be at right angles.

7-3. Ballistic galvanometer and Earth inductor.

(i) Ballistic galvanometer. The total quantity of electricity flowing in a circuit for an extremely short period of time may be measured by a ballistic galvanometer. The ballistic galvanometer is a moving coil galvanometer whose moment of inertia of the movable system is large and whose electromagnetic damping of the swing of the coil is small. Since the period of the swing is longer than the time t which a charge Q takes to pass through the galvanometer, the effect of Q will be to give an impulse to the coil which starts swinging. Again, as the damping of the oscillation is small, the amplitude of swing θ is proportional to Q, that is, $Q=k\theta$ where k is the constant for the galvanometer. k depends on the current sensitivity, the time of vibration of the moving coil, the damping, and the manner in which the discharge is sent through the galvanometer. Thus k is only a constant for any instrument when it is used in one particular way.

(ii) Earth inductor. The earth inductor (Fig. 7.4) is a coil of wire so mounted that it can quickly be given a rotation of 180° about an axis in its own plane. The rotation is controlled by suitable stops. The coil may be used with its plane vertical or horizontal as necessary. It can be used to measure the horizontal and vertical components, H and V, of the earth's magnetic field, and hence also the angle of dip.

Suppose that the plane of the coil is vertical and perpendicular to the magnetic meridian, and that its rotation axis is also vertical. Let n be the number of turns in the coil and A the effective area of each turn. Then the magnetic flux through the coil is due to the horizontal component H of the earth's field. It has the magnitude nAH. If the coil is given half a turn, its direction relative to that of the flux is reversed. This is equivalent to removing the flux and sending it back through the coil in the reverse direction. Hence the change of flux through the coil due to the half turn is $2nAH$. If the coil is connected to a ballistic galvanometer, the half turn will send a charge $Q_H = 2nAH/R$ through the galvonometeter, where R is the total resistance in the galvanometer circuit. Let this charge produce a maximum throw θ_H in the galvanometer. Then $2nAH/R = k\theta_H$

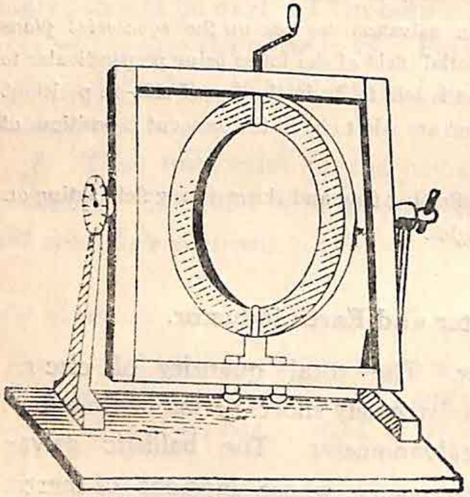


Fig. 7.4. Earth inductor

If the plane of the coil is horizontal, the flux through the coil is due to the vertical component V only. For a half turn, the flux change will be $2nAV$. If this flux change gives a maximum galvanometer throw of θ_V, then $2nAV/R = k\theta_V$, assuming that the galvanometer is working under the same condition as before.

If ϕ is the angle of dip, then

$$\tan \phi = \frac{V}{H} = \frac{\theta_V}{\theta_H}.$$

7.4. To measure the angle of dip using an earth inductor and ballistic galvanometer.

Theory. Let an earth inductor (Sec. 7-3) be placed perpendicular to the magnetic meridian with its plane vertical. It is connected in series with a ballistic galvanometer, the total resistance R in the circuit being enough to make the galvanometer oscillatory. Let an exact half turn of the coil about a vertical axis produce a maximum throw of θ_H in the galvanometer. θ_H is proportional to H, the horizontal component of the earth's field.

The coil is now set in a horizontal plane and given an exact half turn about a horizontal axis. Let the maximum galvanometer throw be θ_V, the total resistance in the galvanometer circuit remaining constant. θ_V is proportional to V, the vertical compopent of the earth's field. The factor of proportionality is the same if R remains constant.

If ϕ is the angle of dip, then

$$\tan \phi = \frac{V}{H} = \frac{\theta_V}{\theta_H}$$

[See the last section (marked 'Earth inductor').]

List of apparatus. Earth inductor ; ballistic galvanometer ; a resistance box of relatively high value (say, up to 5000 ohms) ; a long magnetic needle ; connecting wires.

Instructions. 1. Select a table near which there is no magnetic material nor strong electric current.

2. Place the long magnetic needle on the table, and mark the magnetic north-south direction on the table with a piece of chalk. Draw a perpendicular line to this direction. Place the earth inductor on this line so that the plane of its coil is vertical and in the magnetically east and west direction with the rotation axis vertical.

3. Connect the earth inductor, resistance box and the ballistic galvanometer in series. Put in the resistance box enough resistance to make the galvanometer oscillatory. (You may add a value about 5 times the resistance of the galvanometer. Some

manufacturers state what minimum external resistance will make the galvanometer oscillatory. This is stated as XCDR (External Critical Damping Resistance). If this is known, add a resistance a little more than this. Don't use a much greater resistance. This will make the galvanometer insensitive.) Adjust the resistance in the box to obtain a suitable deflection when the galvanometer is ballistic, that is, swinging freely.

4. Turn the coil rapidly through 180° and note θ_H. Repeat several times and so obtain a mean value for θ_H.

See that the position of the earth-inductor is not changed in any way as you give it a half turn.

5. Without altering the value of the resistance, set the plane of the coil horizontal, with its axis of rotation pointing magnetic east and west. Find an average value of θ_V as the inductor is turned through 180°.

Experimental data

Resistance in the box=···ohms.

Deflections :

Obs.	1	2	3	4	5	6	Mean
Coil vertical							(θ_H)
Coil horizontal							(θ_V)

Result : $\tan \phi = \frac{\theta_V}{\theta_H} = \cdots$

$\therefore$ $\phi = \cdots$(state in degree and minutes).

Method followed : (A brief statement)

1. The magnetic north-and-south line was marked on a table, and so also the magnetic east-and-west. The inductor was placed magnetic east-and-west with the plane of its coil and the axis of rotation both vertical

2. The coil was connected through the resistance box to a ballistic galvanometer. Enough resistance was put in the box to make the galvanometer oscillatory.

3. The coil was then given a half turn (180°) and the galvanometer throw noted. The resistance in the box was adjusted so that the throw was as large as possible for the half turn, while the galvanometer remained oscillatory.

4. Several throws of θ_V were noted and the mean taken.

5. The coil was then placed in a horizontal plane. Several throws were noted for 180° rotations of the coil, and the mean taken.

6. The angle of dip was calculated from the two mean values.

Precautions. 1. The magnetic alignments must be correct.

2. The coil must be given a half turn each time, and that quickly. The time taken in giving the half turn must be small compared with the periodic time of the galvanometer.

3. The half turn is controlled by catches. In giving the half turn, the jerk must not disturb the position of the coil.

4. The total resistance in the galvanometer circuit must remain the same during the experiment. The galvanometer must be oscillatory.

5. There should be no magnetic material or strong electric current near the table.

Oral questions. 1. Define *angle of dip*, and horizontal and vertical components of the earth's magnetic field. How are they related ? What is meant by the *magnetic elements* of the earth ?

2. What is a ballistic galvanometer ? How does it differ from an ordinary suspended coil galvanometer ? What does the former measure ?

3. Why does a charge flow through circuit while there is no battery in it ?

4. Other things remaining the same, how will the galvanometer throw change when

(i) the number of turns in the coil is increased .

(ii) area of the turns is increased :

(iii) the coil is turned slowly ?

5. Is the dip angle the same everywhere on the earth ? When do we call it positive and when negative ? What are its values on the magnetic equator and the magnetic poles ?

Answers. 1. The angle which the direction of the earth's magnetic field makes with the horizontal in the plane of the magnetic meridian is called the angle of dip.

The horizontal component of the earth's magnetic field is the resolved part of the earth's magnetic intensity in a horizontal direction in the magnetic meridian.

The vertical component is the resolved part of the intensity in the vertical direction.

The three quantities, such as magnetic declination, angle of dip and horizontal intensity, which define completely the earth's magnetic field at any point, are called magnetic elements.

2. See Sec. 6-4(i). It measures the charge which flows through it for a duration short enough compared with the periodic time of its oscillation.

3. The change of flux that takes place through the coil creates an emf. It lasts so long as the flux is changing. This emf drives a short-duration current, hence charge, through the circuit.

4. (i) Throw increases as the flux change increases with increase in number of turns of the coil.

(ii) Throw increases as the flux change increases with increase in area of the coil.

(iii) Induced emf is proportional to rate of change of flux. If flux change occurs slowly induced emf will be less. But if the time period of the galvanometer is very large compared with the total time taken for the rotation of the coil, the throw will not be affected (as in a fluxmeter).

5. No. When the north pole of a freely suspended magnet dips downwards, as in most part of the northern hemisphere, dip is called positive. When the south pole dips downwards it is called negative.

At the magnetic equator, dip=0°(that is, a freely suspended magnet remains horizontal). At the magnetic north pole, dip=+90°(that is the north pole of the magnet dips vertically downward). At the magnetic south pole, dip=−90°(that is the south pole of the magnet dips vertically downward).

CHAPTER 8

ELECTRICAL ACCESSORIES AND INSTRUMENTS

8·1. Simple electrical accessories

In performing an electrical experiment various simple electrical accessories are required. some of those most commonly used are described below.

A. Keys are simple devices for making or breaking a circuit. Fig. 8.1 represents a simple *plug key.* It has two brass blocks with binding screws attached to them. The blocks are mounted on an ebonite base, and are seperated by a small air gap and a conical hole. A brass plug with a ebonite top fits into this hole. When the plug is inserted, metallic connection is established between the terminals of the blocks, which are connected to the circuit. It acts as a switch ; but *it should not be used in a circuit powered by supply mains*, because the air gap is small and breaking the circuit will start an arc across the gap.

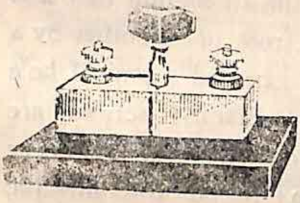


Fig. 8.1

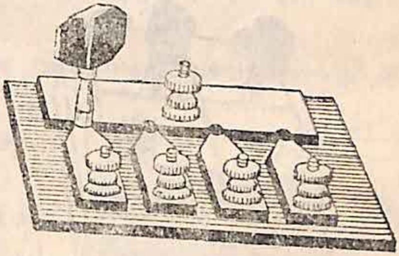


Fig. 8.2

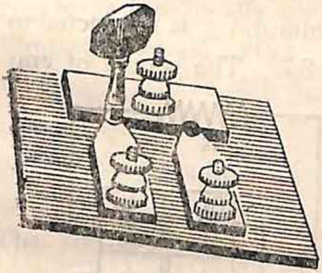


Fig. 8.3

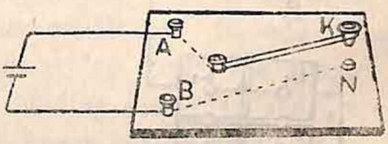


Fig. 8.4

Sometimes it is necessary to send a current when desired through one or two or more alternative paths. Two-way and four-way keys are used for the purpose. Their construction will be understood from Fig.s 8.2 and 8.3.

A *tapping key* (Fig. 8.4) closes a circuit only when its knob (K) is pressed. Its action will be understood from the figure.

B. A **Commutator** is a device for reversing the current through a circuit or a part thereof without changing the connections. There are various types of which those most commonly used are (i) the *plug type commutator* and (ii) *Pohl's commutator*.

(i) **Plug type commutator.** It consists of four blocks of brass (making up a square or a circle) mounted on an ebonite base and separated from one another by a small air gap and a conical hole (Fig. 8.5). Binding screws are attached to each block. Adjacent blocks may be put into metallic contact by inserting a brass plug into the hole between them.

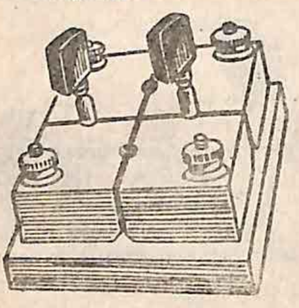


Fig. 8.5

The way in which a plug type commutator is connected to a circuit is illustrated in Fig.s 8.6. and 8.7. The source of emf

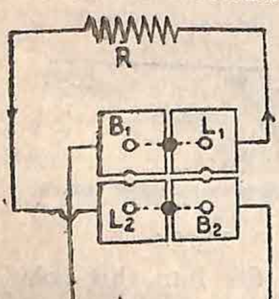


Fig. 8.6

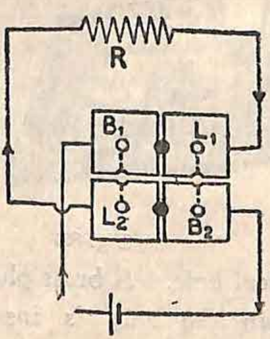
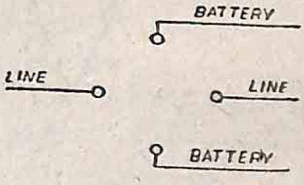


Fig. 8.7

(here the battery) is connected to a pair of *diagonally opposite* segments (B_1, B_2) of the commutator. The terminals of the line in which the current is to be reversed are connected to the other pair (L_1, L_2). If two plugs are inserted in a pair of opposite holes as shown by the deep circles in Fig. 8.6, the current from the battery passes from B_1 to L_1 through the plug. After traversing the circuit as shown, it passes form L_2 to B_2 through the other plug and returns to the battery. If the plugs are taken off and inserted in the other pair of opposite holes as in Fig. 8.7 it will be seen that the current now flows through R in the reverse direction.

While changing the plugs for reversal, take care to *remove both plugs* before re-inserting any one of them. Otherwise there is a risk of the battery being short-circuited. (Suppose in Fig. 8.7, the plug between B_1 and L_2 is removed and reinserted between B_1 and L_1 before the other plug has been removed. It will short-circuit the battery.)

Diagrammatically a plug type commutator is represented in the manner shown in Fig. 8.8. The circles represent the binding screws ; the holes are not indicated.



Fig, 8.8

(ii) **Pohl's commutator,** It has an ebonite base provided with six small holes (cups) cotaining mercury, each cup being metallically connected to a binding screw (Fig. 8.9). An important part of the commutator is the 'rocker' which has a horizontal ebonite handle connecting two sets of metal legs, three on each side. The outer legs on either side are a little shorter than the middle legs. So when the rocker rests in the cups, only four of its legs touch the mercury. The mercury cups leading to the binding screws L_1 and l_1 are conected together by a short piece of copper wire or strip. So also are the cups leading to L_2 and l_2. These two connecting pieces are insulted from each other.

The screws B_1 and B_2 are connected to the battery, while the ends of the line in which the current is to be reversed are connected *either* to the pair of screws L_1, L_2 *or* to the pair l_1 and l_2.

When the rocker rests on one side the current flows through the line in one direction. When the rocker is thrown over to the other side the current through the line is reversed.

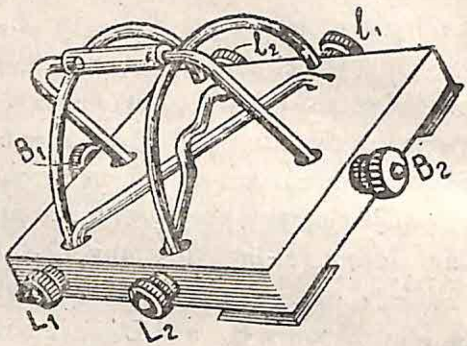


Fig. 8.9

Diagrammatically, a Pohl commutator is represented as in Fig. 8.10 where the circles represent the mercury cups.

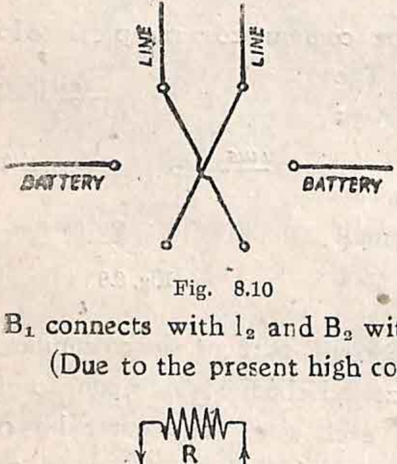


Fig. 8.10

The process of reversal may be understood by reference to Figs. 8.11 and 8.12. When the rocker is thrown over to the side of L_1, L_2 metallic connection is established between B_1 and L_1 and between B_2 and L_2. When thrown over to the side of l_1, l_2, B_1 connects with l_2 and B_2 with l_1.

(Due to the present high cost of mercury, and the reckless way students spill it, it is doubtful if you will be given a Pohl commutator to work with.)

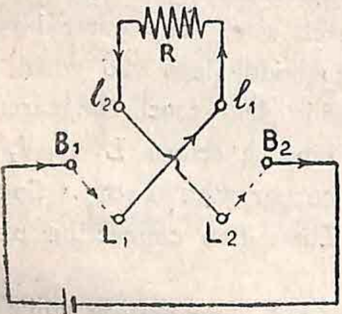


Fig. 8.11

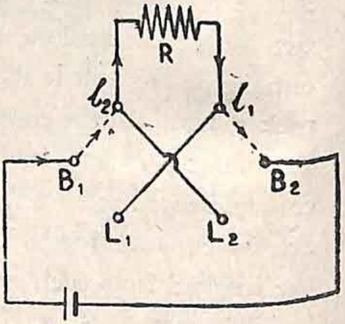


Fig. 8.12

C. Fixed-resistance coils. Coils of wire having fixed known resistances (in ohms) are largely used in electrical measurements. Two brass terminals (A, B, Fig. 8.13) are fixed in a plate of ebonite or vulcanite. The ends of a piece of enamelled, silk-covered or double-silk-covered wire (W) having the necessary resistence are soldered to them. The wire is doubled on itself and wound on a wooden bobbin impregnated with wax (or on ebonite or porcelain bobbins). *This kind of winding reduces self-induction to a minimum.* Due to doubling, the current in adjacent portions of the wire flows in opposite directions. The magnetic field due to current in one half of the coil is thus practically neutralised by that in the other half.

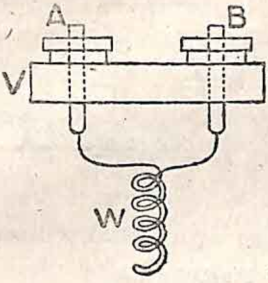


Fig 8.13

For small resistances the wire is short and thick ; for large resistances it is long and thin. The completed coil is given a protective non-conducting coating of varnish or wax.

Manganin (an alloy of about 84 Cu, 4 Ni and 12 Mn) is generally used as the material of the wire. It has a fairly high specific resistance (about 42 microohm cm) and an *almost zero temperature coefficient of resistance.* Hence the resistance of a coil made of this material remains practically constant at different temperatures.

D. Standard resistance. These are resistance coils of fixed value, very carefully constructed so as to represent the stated value as closely as possible. The external appearance and the internal arrangement, are shown in Figs. 8.14 and 8.15. The leads are two hookshaped copper rods, whose resistance is negligibly small. They are hung from mercury cups when in use. Some types have

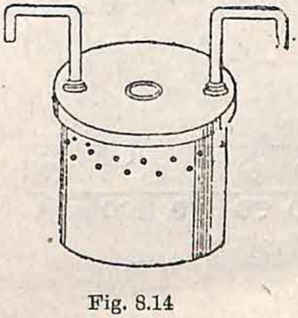


Fig. 8.14

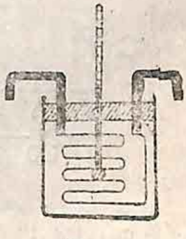


Fig. 8.15

binding screws attached to the leads. For precision work a thermometer is inserted into the coil.

E. Resistance boxes. A resistance box consists of a number of fixed-resistance coils so mounted in a box that any number of them can be used at a time *in series*. The coils are constructed in the way already mentioned under 'Fixed-resistance coils'. The ends of a coil are soldered to two brass pins connected to two brass blocks mounted on a sheet of ebonite or vulcanite. The blocks (M, Fig. 8.16) are separated from each other by a small air gap and a conical hole in which a conical brass plug with an ebonite tap fits in. When a plug (P) is put in a gap (G), the coil connected across the gap is short-circuited by the plug. The whole of the current then passes from one block to the other through the plug, and practically nothing flows through the coil. The coil thus becomes inoperative. When the plug is taken out the current passes from one block to the other through the resistance coil.

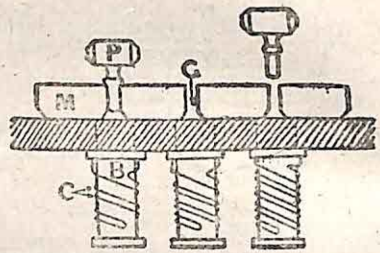


Fig.8.16

Fig. 8.17 shows a diagrammatic arrangement of the brass blocks and the holes separating them. A and B are the terminals of the resistance box. The number written down near a hole gives in ohms the resistance of the coil connecting the blocks on two sides of the hole. For the values in the figure, the resistance between A and B can be given any integral value between 1 ohm and 420 ohms.

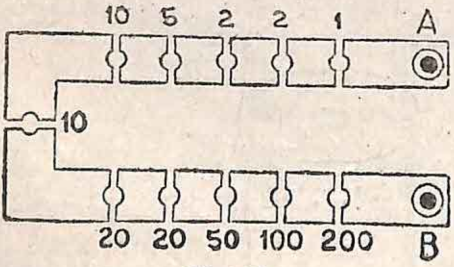


Fig.8.17

The boxes are made in various ranges. The resistances are generally *multiples* and *submultiples* of an ohm.

When all plug of a resistance box are secured tightly in position, the effective resistance of the box between its terminals is negligibly small. As soon as a plug is taken out, the resistance of the corresponding coil is included between the terminals of the box. The values for different coils add up in series.

When using a resistance box all plugs other than those opened, must be secured fairly tight. If any plug is loose it introduces an extra resistance which cannot be taken into account.

F. Dial pattern resistance box. In the dial pattern resistance box (Fig. 8.18), now frequently met with in the laboratory, a number of metal studs are arranged at equal distances on an arc of a circle on the ebonite lid of the box. Neighbouring studs are connected together *in series* by resistance coils of appropriate values placed within the box, The studs are marked 0, 1, 2, to 10 round the arc. In going from one stud to the next, the resistance increases by equal amounts, generally an ohms or a multiple or sub-multiple thereof. (This value is imprinted on the lid.) The stud marked zero is connected to one of the terminals of the box. A rotating contact arm connected to the other terminal of the box establishes metallic contact (through wires or strips of negligible resistance) between this terminal and any of the studs. Thus when the contact arm is placed on stud 2, the resistance included between the terminals of the box is 2 units of the value imprinted on the lid.

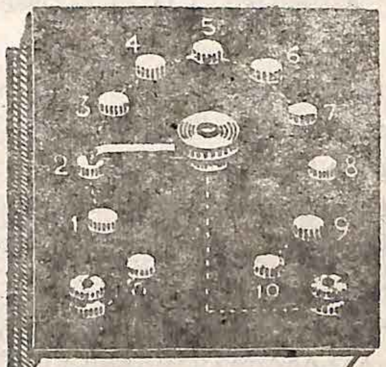


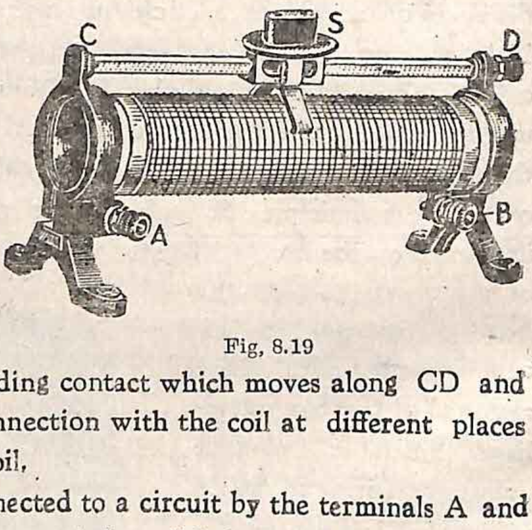
Fig. 8.18

The *total value* of the resistance between the stud marked zero and a given one is imprinted by the side of the given stud.

A box may have several dials of this kind, marked (say) ×1, ×10, ×100. The first dial is for values changing by one ohm ; the second, by 10 ohms and the third, by 100 ohms. To make up a resistance of 973 ohms, the contact arm of the first dial is set on stud 3, of the second on 7 and of the third on 9.

G. Rheostats or variable resistances. A rheostat is a resistance whose value can be changed *almost* continuously (not like resistance boxes where the change is discontinuous). It may be of the *sliding* or the *rotary* type.

A sliding rheostat (Fig. 8.19) consists of a coil of bare (manganin or eureka) wire wound in a thin, narrow groove, cut uniformly round a cylinder, generally of porcelain. The successive turns are insulated from each other. The ends of the coil are connected to two terminals A and B. CD is a metal rod with a terminal at D. S is a sliding contact which moves along CD and brings it into metallic connection with the coil at different places along the length of the coil.



Fig, 8.19

If the rheostat is connected to a circuit by the terminals A and B, the whole of the resistance of the coil is included in the circuit, and no variation of resistance can be made by moving. S. But if the connections are at A and D, the actual resistance included in the circuit depends on the position of S (see Fig. 8.20).

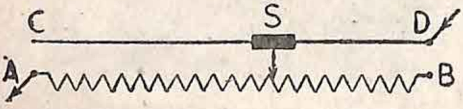


Fig. 8.20

The effective portion of the coil is from A to the point of contact of S on the coil. By sliding S resistance can be changed almost continuously.

In a rotary rheostat the coil is wound on a circular non-conducting frame (Fig. 8.21). A revolving switch arm turned by a milled head makes contact at different places of the coil. Terminals are attached to the ends of the wire (or one end) and the switch arm. When a circuit is connected to one end of the coil and the switch arm, variation of resistance can be introduced by turning the switch.

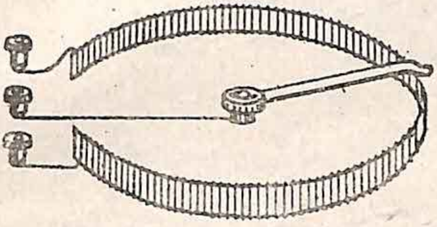


Fig. 8.21

A rheostat is represented diagrammatically as in Fig. 8.22(a) or (b).

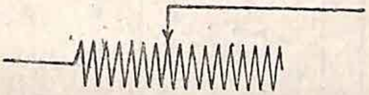


Fig. 8.22(a)

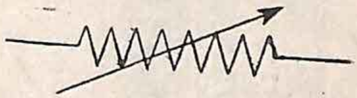


Fig. 8.22(b)

8-2. The moving coil galvanometer.

Galvanometers belonging to this class have one feature in common : in all of them the current to be detected or measured flows through a coil which can move in the magnetic field due to a permanent magnet. The way in which the coil is mounted differs in different types.

8-2.1. Suspended coil D' Arsonval type galvanometer

This type is very common and it is frequently used in the laboratory. It consists of a rectangular coil (C, Fig. 8.23) of many turns of fine, insulated copper wire suspended by means of a fine strip (A) of phosphor-bronze. The upper end of the strip is soldered to a torsion head supported on a brass pillar. This pillar is connected by an insulated wire to one terminal of the galvanometer.

One end of the wire making up the coil is soldered to the lower end of the strip, while the other end is attached to a fine spiral of phosphor-bronze. The spiral is soldered to a brass piece projecting from the brass pillar, but insulated from the latter. This

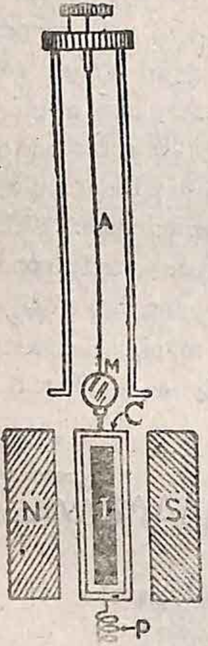
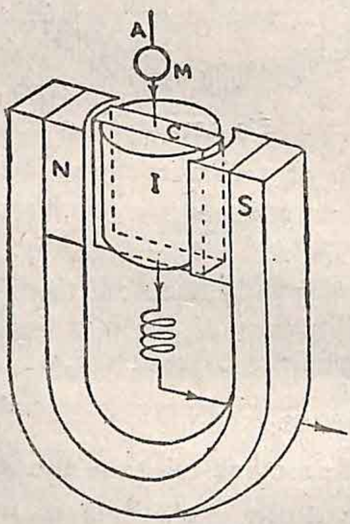


Fig. 8.23



Fig, 8.24

brass piece is connected to the other terminal of the galvanometer. The current thus passes through the suspension, coil and spiral.

In the normal position the coil hangs freely in a cylindrical cavity between the concave pole pieces (N, S ; Fig. 8. 24) of a permanent horse-shoe magnet. The axis of suspension of the coil is coaxial with this cylindrical cavity. A soft iron cylinder (I) is placed coaxially with the pole faces and is rigidly attached to the brass pillar previously mentioned. The coil lies outside this cylinder and can rotate freely in the annular air gap between it and the pole faces.

The purpose of the cylindrical pole faces is to provide a radial field, *i e.,* a field of which the lines of force in a transverse section are directed along the radii of a circle (see Fig. 8.25 which represents a transverse horizontal section through I, NS and the vertical limbs of the coil). *The soft iron cylinder improves the radial nature of the field and, further, increases its strength.* The smaller the air gap between the pole faces the stronger the field between them.

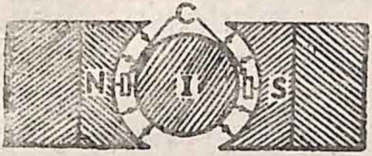


Fig. 8.25

In order to protect the coil from air currents the instrument is enclosed in a cylindrical brass cover with a glass window. Fig. 8.26 shows the instrument with the cover removed. A small plane or concave mirror (M) is attached near the top of the coil. A beam of light is reflected from this mirror and is received on a scale. The motion of the spot of light indicates the rotation of the coil.

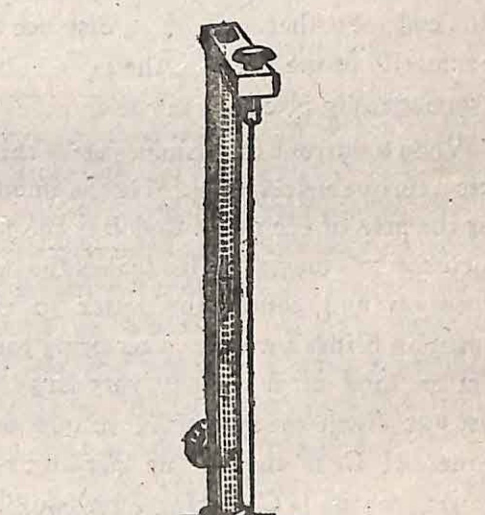


Fig. 8.26

The instrument is supported on three levelling screws. They are so adjusted that the coil moves freely and symmetrically in the annular air gap between I and NS without touching any one of them. When necessary, the coil can be locked by a spring (having the shape of a tongue) which lies between the coil and the top of I. The spring is operated by a milled head attached to the base of the instrument.

8-2.2. Theory. Because of the radial nature of the field the lines of force are parallel to the plane of the coil for all positions of the coil. The lines are also perpendicular to the vertical limbs of the coil. Further, at a given distance from axis of the cavity the intensity of the field has the same value. Hence when the coil is symmetrically placed, it moves in a field of constant intensity.

When a current of i e.m.u. passes through the coil, it experiences a torque $nABi$, where n is the number of turns of the coil, A is the area of each turn and B is the *flux density* of the field in which the coil moves. This makes the coil rotate about its axis of suspension and causes the latter to twist. The twist of the suspension brings into play a restoring torque proportional to the twist so long as it is not very large. Equilibrium occurs for a twist θ at which the restoring torque is equal to the deflecting torque. If C is the torque per unit twist of the suspension, the restoring torque is $C\theta$. Hence for equilibrium

$$nABi=C\theta \quad \text{or} \quad i=\frac{C}{n.AB}\,\theta=K\theta \tag{8-2.1}$$

K is a constant for a given galvanometer and is called the *constant of the galvanometer.* Eq. 8-2.1 shows that for a given current θ will be larger the smaller the value of C and the larger the values of n, A and B.

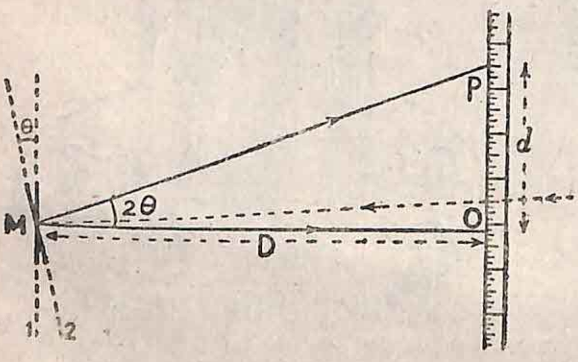


Fig. 8.27

8-2.3. Measurement of small rotation of the coil. To measure a small rotation θ where necessary we make use of a lamp and scale arrangment. A beam of light is reflected from the mirror attached to the coil and forms a sharp image of a line (or a slit) on a scale placed at a distance. If the mirror turns by θ, the image is displaced by 2θ (Fig. 8.27). If d is the displacement of the the image and D the distance of the scale from the mirror then $\tan 2\theta = d/D$. If θ is small we can take $2\theta = d/D$. When $D = 1$ metre and $d = 10$ cm, the error in taking $\theta = d/2D$ is about 0·2%. If d is 20 cm the error is 1·25%.

8-2.4. *Dead beat motion of a galvanometer coil.* When a galvanometer coil is deflected from its position of rest or from one of steady deflection, and is allowed to reach the final position it may reach the final position after executing a few oscillations or gradually approach the final possition without overshooting it. In the former case its motion is said to be oscillatory ; in the latter case the motion is **dead beat** (or *aperiodic*). In most experiments we prefer a dead beat motion than an oscillatory one since it comes to rest more quickly. This is affected by winding the coil on a closed aluminium frame. As the coil rotates in the magnetic field, currents induced in the closed metal frame oppose the motion of the coil and soon bring it to a stop. But this does not change the final position of rest since the induced current ceases along with the motion of the coil.

If the motion of a galvanometer coil is oscillatory, it can very often be rendered dead beat by short-circuiting the terminals of the galvanometer. A tapping key connected across the terminal will be found very useful for this purpose. If it is *kept pressed*, the coil, instead of oscillating, will gradually approach the position of rest. The approach to the final position will be quickest if the tapping key has in series with it a resistance known as the *external critical damping resistance*. Its value depends on the construction of the galvanometer and is generally supplied by the makers.

8-2.5. Adjustments and tests of a galvanometer before use.

The following **adjustments** should be made before a galvanometer is used :

(i) The galvanometer coil should first of all be released from the clamp.

(ii) It should be levelled by the levelling screws so that the coil moves freely in the annular air gap between the pole faces and the soft iron cylinder without touching any one of them.

(iii) The positions of the lamp, scale and focusing device should be adjusted so that a sharp image is formed in the centre of the scale. The torsion head from which the coil is suspended may be rotated to bring the image to the centre.

The following **tests** should also be made :

Send a small current (a few microamperes) through the coil. The spot of light on the scale should move to the final position smoothly without jerk. Reverse the current. The spot should move to the same distance on the other side of the zero. If the motion is jerky or unequal on two sides more careful levelling of the galvanometer is necessary.

8-2.6. Sensitivity of a Galvanometer. When a weak current produces a large deflection in a galvanometer, it is said to be *current sensitive.* When a small voltage applied across its terminals produces a large deflection it is said to be *volt-sensitive.*

The **current sensitivity** or the *figure of merit* of a galvanometer is defined as the current required to produce a deflection of 1 mm on a scale at a distance of 1 metre from the galvanometer mirror. The smaller this value the more sensitive the galvanometer.

Current sensitivity is increased (i) increasing the number of turns of the coil or (ii) using more delicate suspension. In the former case the resistance of the galvanometer coil increases. Galvanometers of high current-sensitivity generally have a high resistance.

D' Arsonval galvanometers ordinarily used in the laboratory have a figure of merit of the order of 10^{-8} amp per division and a resistance of the order of 10^{2} ohms.

The **volt sensitivity** of a galvanometer may be defined as the potential difference in volt to be applied across the terminals of the galvanometer so as to produce a deflection of 1 mm at a scale distance of 1 metre. According to this defination we have

Volt-sensitivity (S_v) = figure of merit × galvanometer resistance.

A volt-sensitive galvanometer should therefore have a low resistance.

To decide which of several galvanometers has the greatest *current sensitivity*, we may connect them *in series* and send a current through them. The one which gives the largest deflection has the greatest current sensitivity.

To test *volt sensitivity*, we may connect them *in parallel* and apply the some voltage to all. The one which shows the largest deflection has the greatest volt sensitivity.

Example. The resistances of two galvanometers are respectively 1000 ohms. and 5 ohms. Their figures of merit are 1×10^{-8} and 1×10^{-6} amp. per division respectively. Which has the higher volt sensitivity ?

S_v of the first $= 1 \times 10^{-8} \times 1000 = 10$ microvolts per div.

S_v of the second $= 1 \times 10^{-6} \times 5 = 5$ microvolts per div.

The second has double the volt-sensitivity of the first.

Current-sensitivity is also measured by the amount of deflection in millimeters when a current of one microampere passes through the coil, the scale being at the standard distance of one metre.

Similarly, volt-sensitivity is measured by the defletion in millimetres when a potential difference of one microvolt is applied across the terminals of the galvanometer, the scale being one metre away.

These definitions provide values which are reciprocals of values obtained by the previous definitions, provided that the current and voltage are measured in micro units.

Though both definitions are in use, they will cause no confusion if the value is expressed in proper units. Thus the statements that the 'sensitivity of galvanometer is 12 divisions per microampere' or '0·08 microampere per division' are equally explicit.

For most null point work we require a volt-sensitive galvanometer.

8-27. Protection of galvanometers : Galvanometer shunts.

A galvanometer is a very delicate instrument and must be protected against the flow of relatively large currents through it. A large current may burn the spiral, snap the suspension or damage the coil. *The necessary protection may be given*

(i) *either* by connecting a suitable **low resistance in parallel as a shunt** to the galvanometer,

(ii) *or* by connecting a suitable **high resistance in series with** the galvanometer.

Shunt. A low-resistance box containing fractions of an ohm may be used as a shunt. A simple plug key should be connected in series with the box and the combination connected across the galvanometer terminals. Fig. 8.28 shows the connections. R. B. is the low resistance box, K the key and G the galvanometer.

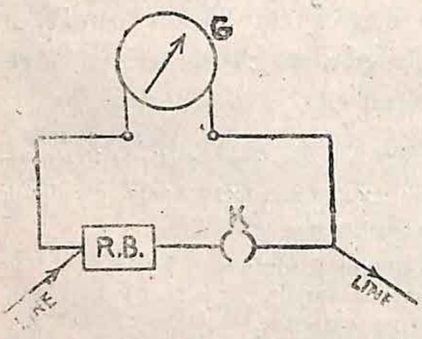


Fig. 8.28

When the key is open, the entire current passes through the galvanometer. The shunt is then inoperative.

When all the plugs of the resistance box are in position and so also the plug of the key, the shunt has a negligibly small resistance. Practically the whole of the current then passes through the shunt and none through the galvanometer.

To have a suitable shunt, a suitable resistance should be opened in the box while the plug of the key is in position. *To cut out the shunt, remove the plug of the key.*

If your galvanometer is too sensitive use a lower resistance as shunt. If it is not enough sensitive increase the resistance of the shunt.

Series resistance. A resistance box having values up to 5,000 or 10,000 ohms may be used with profit in series with the galvanameter to afford it the necessary protection. This will reduce the sensitivity of the galvanometer. When higher sensitivity is required this resistance may be cut out by inserting the plugs.

8-2.8 Portable moving coil galvanometers. These moving coil galvanometers are similar in construction to the suspended coil galvanometer already described, but differ from the latter in the mode of mounting of the coil. They are less sensitive than suspended coil galvanometers and are used when high sensitivity is not necessary.

The coil is supported on two jewelled pivots (Fig. 8.29) by means of two short metal spindles attached symmetrically to the coil. The ends of the coil are soldered to the spindles.

The controlling couple is exerted by two hair springs of phosphorbronze ends of the springs are soldered to the wound in opposite directions. The inner spindles and the outer ends are attached to two insulated terminals fixed to the body of the instrument. These in their turn are connected to the terminals of the galvanometer.

Since the springs are wound in opposite directions, the changes which they suffer due to variation of temperature act on the coil in opposite directions and produce no effect on the position of the coil. For this reason there will be no shift of zero due to change of temperature. The springs not only exert the controlling couple but also serve as leads for conveying the current to and from the coil.

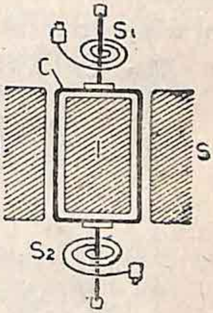


Fig. 8.29

A long aluminum pointer is attached to the upper spindle and moves over a graduated circular scale. The graduations are arbitrary. The zero of the scale is at the middle. In the normal position of the coil the pointer stands at zero.

At the other end the pointer extends a little beyond the spindle and has a forked end. The forks carry two adjustable weights by which the centre of gravity of the moving system may be brought on the axis of rotation. In such a case gravity plays no part in determining the position of the coil. The instrument may therefore be placed on the table in any position, without the position of the coil changing in any way due to gravity.

These galvanometers are very compact in size and require no initial adjustments. Their sensitivity varies from 10^{-5} to 10^{-6} ampere per division of the scale.

8-3. The moving coil ammeter

An ammeter is a commercial instrument for measuring an electric current directly in amperes. The moving coil ammeter is a moving coil galvanometer of the pivoted type except that it has a low-resistance shunt connected across the terminals of the coil. The scale is calibrated in amperes, and is an essential part of the instrument.

The coil (C, Fig. 8.30) is rectangular and made of fine insulated copper wire. It is wound on a light frame and mounted in jewelled bearings between the poles (N, S) of a strong, permanent horse-shoe magnet (M). The pole faces are cylindrical, the air gap between them being reduced by a soft iron cylinder (I) coaxial with the pole faces. The coil moves in the narrow annular air gap between I and NS. The current is led into and out of the coil by two fine spiral springs, one (S_1) above the coil and the other (not

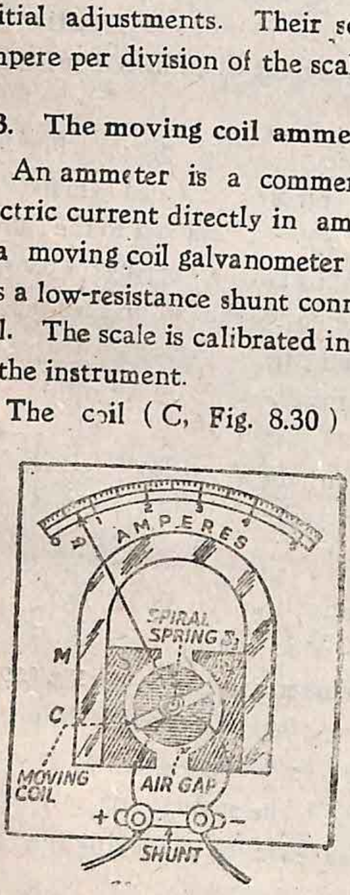


Fig. 8.30

shown in the diagram) below it. The springs are wound in opposite directions and supply the opposing torque. They are connected to the terminals A and B of the instrument. A and B are also connected to the ends of a low-resistance shunt which is in the form of a metal strip.

A long needle (P) attached to the coil moves over a properly graduated scale and gives the value of the current in amperes. The deflection of the needle is proportional to the current. The scale is an essential part of the instrument.

The action of the springs on the position of the coil and the method of neutralising the effect of gravity on the latter are the same as in the portable moving coil galvanometer of the pivoted type (see Sec. 8-2.8)

The shunt carries the greater part of the current and reduces the effective resistance of the instrument. That the resistance of the instrument should be low is a necessity, as otherwise its insertion in the circuit would alter the value of the current which it is required to measure. If G is the resistance of the coil and S that of the shunt a fraction $S/(G+S)$ of the total current passes through the coil.

By altering the value of the shunt the range of the instrument may be extended. Different shunts may be provided for the purpose with the same galvanometer. The same purpose may be served by connecting extra terminals to different points of a single shunt connected across the terminals of the coil. Compact multirange ammeters are of this type.

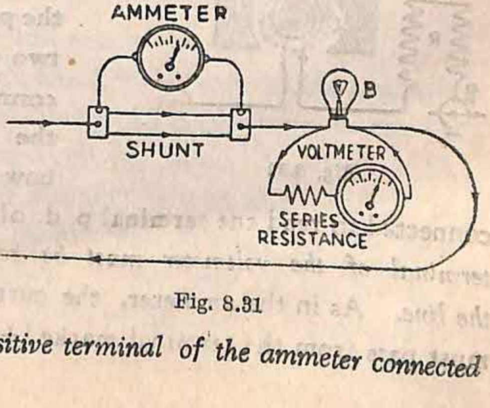


Fig. 8.31

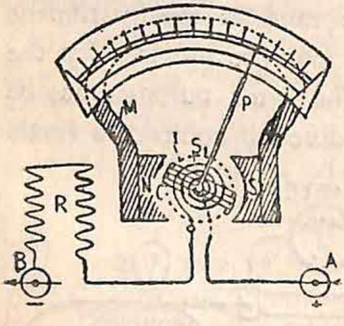
To measure a current in a circuit by an ammeter, the latter must be connected in series. For this purpose *the circuit may be opened anywhere and the positive terminal of the ammeter connected* *to the positive side of the line.* Within the ammeter the current must flow from the terminal marked + to the terminal marked—. (The latter may also be unmarked.) A wrong connection may damage the needle. Fig. 8.31 shows a way in which an ammeter may be connected to measure the current flowing through the bulb B. It may be on either side of B.

8·4. The moving coil voltmeter.

Direct current voltmeters ordinarily used in the laboratory are of the moving coil type. Their construction is exactly similar to that of an ammeter ; the only difference is that *while the ammeter has a low resistance in parallel with the coil, the voltmeter has a high resistance in series with the coil* (Fig. 8.32). This high resistance is incorporated within the instrument.

When a voltmeter is connected across points differing in potential by V, a small current $I=V/R$ passes through the coil. R is the resistance of the entire instrument and should have a large value. Otherwise its insertion may alter the very potential difference which it is required to measure.

The current causes a deflection of the coil and hence of the pointer on the scale. Since R is fixed for a given instrument, the deflection of the pointer can be calibrated directly in volts.



Fig, 8.32

A voltmeter always records the potential difference between its own terminals. To measure the potential difference between two points of a circuit, it is connected in parallel across the points. Fig. 8.31 shows how a voltmeter should be connected to read the terminal p. d. of the bulb B. *The positive terminal of the voltmeter must be connected to the positive side of the line.* As in the ammeter, the current through the voltmeter must pass from the terminal marked + to the other.

By using different values of the series resistance the range of a valtmeter may be extended. The compact multi-range voltmeter has a single high resistance to which terminals are attached at different points.

By using different values of the series resistance the range of voltmeter may be extended. The compact multi-range voltmeter has a single high resistance to which terminals are attached at different points.

The higher the resistance of a voltmeter per volt of its range the more correct is its reading. Good instruments have a resistance of 1,000 to 2,000 ohms (or even more, up to 20,000 ohms) per volt.

Test yourself

(On galvanometers, ammeters and voltmeters)

(i) Describe the construction of a moving coil galvanometer. (ii) What part does the soft iron cylinder play ? Does it move with the coil ? (iii) Why are the pole faces cylindrical ? Is a magnet essential for the galvanometer ? What is it made of ? (iv) What are the suspension and the spiral made of ? Will it do if the suspension be of silk or quartz ? (v) Why is the suspension made of a thin strip and not a cylindrical wire ? How does the sensitivity depend on the suspension ? (v) Why can't you allow a large current to pass through a galvanometer ? What precaution would you take for it ? What is a dead-beat galvanometer ? How can you check the oscillations of the coil ? Explain how the device that you suggest checks the motion. (viii) State what is common to galvanometers, ammeters and voltmeters. How do they differ ? (ix) Why should the resistance of an ammeter be low and that of a voltmeter high ? Have you any idea of the order of magnitude of the values ?

(It you are not sure of the answer, consult the earlier portions.)

8-5. Primary and secondary cells

A *primary cell* is a device by which the energy made available by chemical reactions may be converted into electrical energy. The Daniell cell, the Leclanche cell, the Standard Cadmium cell, etc., are examples. The total amount of electrical energy or charge available from any of these cells depends on the total amount of the reacting materials. When any of the reacting materials is exhausted, the cell ceases to function. To restore an exhausted primary cell to life, fresh material has to be introduced.

A *secondary cell*, *storage cell*, or *accumulator* is a device from which an electric current may be drawn for a certain time as from a primary cell ; but, unlike the primary cell, when the accumulator is exhausted it may be restored by sending an electric current through it in a direction opposite to that in which the cell itself drives the current. At discharge, the energy conversion was from chemical to electrical. At charging, electrical energy is stored as chemical energy in the cell.

8·6. Accumulators

Accumlators can give steadier and stronger currents. There are two principal types used in the laboratory,—(i) the *lead accumulator* (or *lead-acid cell*) and (ii) the *nickel-iron-alkali cell*, also called the *Edison cell*.

8·6.1 Lead accumulator. In a commercial cell which has been charged and is ready to deliver a current, the negative electrode consists of a plate having a grilled structure, filled with spongy lead. The positive electrode, having a similar sttucture, is filled with packets of porous lead peroxide (PbO_2). The plates are immersed in an electrolyte of dilute H_2SO_4 (about 20%) contained in a glass vessel (Fig. 8.33).

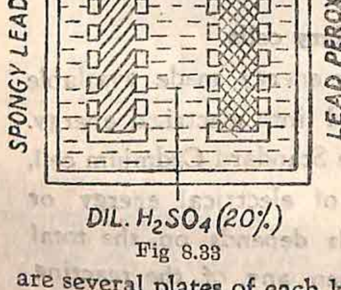


Fig 8.33

The *capacity* of a cell is increased by increasing the working surface of the plates. Thus the greater the number of plates in a cell and the larger their surface, the greater wil be the capacity and the current output.

In cells of larger capacity there are several plates of each kind. The positive and negative plates are arranged alternately, each group being connected at the top to a lead bar. Neighbouring plates are separated by glass or wooden separators.

The negative group contains one plate more than the positive group (Fig. 8.34) except in a two-plate cell.

Since the plates are close together and have large areas, the internal resistance of the cell is very small.

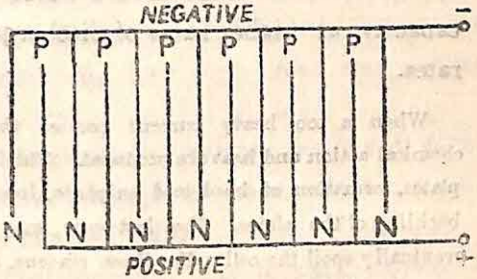


Fig. 8.34

EMF. The emf of a single cell, *large* or *small*, is almost exactly 2 volts. During discharge the voltage diminishes very slowly at first, but more rapidly later when the cell is nearing exhaustion (Fig. 8.35). If the emf falls below 1·9 volts, the dischange should be stopped and the cell recharged. Otherwise, it may undergo a permanent damage ; this is due to the lead and lead peroxide being permanently converted into white lead sulphate. It reduces the capacity of the cell. **The voltage of a cell should be tested in closed circuit after it has been driving current for a few minutes.** In open circuit even a fairly exhausted cell may indicate 2 volts.

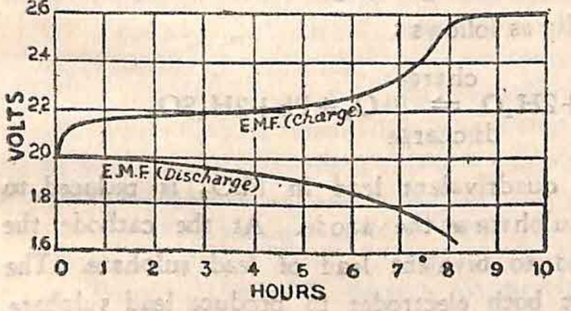


Fig. 8.35

Capacity. The capacity of an accumulator is expressed **in ampere hours.** It is the product of the current (in amperes) which the cell can deliver and the time (in hours) for which the current may be drawn. If the capacity of a cell is given as 60 amperehours, it can give a current of 1 amp for 60 hrs, or 2 amps for 30 hrs and so on. But there is a limit to the maximum current which should be drawn from a cell. The maximum discharge rate is specified by the makers and should never be exceeded. The effective capacity at higher rates of discharge is smaller than that at lower rates.

When a too heavy current passses through a lead accumulator, intense chemical action and heat are produced. This results in unequal expansion of the plates, formation of hard lead sulphate, loosening of the active material and buckling of the plates. The last one may produce internal short-circuit and eventually spoil the cell. For these reasons, *the lead accumulator should never be short-circuited outside nor a current drawn from it in excess of the maximum discharge rate* (specified by the makers). The maximum discharge rate of an old cell is smaller than that of a new one.

Besides the voltage, the specific gravity of the H_2SO_4 solution is also affected during discharge. For a fully charged cell the specific gravity is abont 1·24. The exact value depends on the make. When half discharged the value falls to about 1·17 and near full discharge to about 1·11. To be on the safe side the cell should be recharged when the specific gravity fall to 1·15.

When fully charged the emf is a little over 2 volts—frequently 2·2 volts. During discharge the value quickly falls to 2 volts, remains practically constant at that value for a pretty long time and gradually falls. So, *when a steady emf is required, neither a freshly charged lead cell nor one near exhaustion should be used.*

The chemical changes during charge and discharge may be represented symbolically as follows :

$$2PbSO_4+2H_2O \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} PbO_2+Pb+2H_2SO_4$$

During discharge quadrivalent lead in PbO_2 is reduced to bivalent lead of lead sulphate at the anode. At the cathode the lead atom is oxidised to bivalent lead of lead sulphate. The sulphion combines at both electrodes to produce lead sulphate. Hence the specific gravity of the acid falls with discharge.

During charge the $PbSO_4$ at the two electrodes is converted into Pb and PbO_2. This sulphate is different from the permanent or hard sulphate which forms when the cell is damaged.

In the charged cell positive plate appears dark brown or chocolate in colour (due to the peroxide), while the negative plate is grey—a pale grey. When discharged the positive plate is pale chocolate and the negative dark grey in colour.

How to choose your cell. The lead accumulators in a laboratory are often found in different conditions of charge and fitness for service. To choose the best one for your work remember the following :

(i) Avoid cells which have much sediment at the bottom, whose plates have peeled off, are buckled or have white deposits on them. Also avoid freshly charged cells.

(ii) Prefer a cell whose positive plate has a dark brown or chocolate colour and the negative, pale grey.

(iii) Test the voltage in closed circuit. The value should be close upon 2 volts but not appreciably higher, and also not lower than 1·9 volts.

(iv) When a current of 1 ampere or more is to be drawn, choose a large cell. Keep well below the maximum discharge rate. A small cell may be used for driving the current in a potentiometer circuit.

Test yourself

(i) What is a storage cell ? Does it store electricity ? How does it differ from a primary cell ? (ii) Describe the structure of a lead accumulator. What are the materials consisting the anode, cathode and the electrolyte ? (iii) What do you understand by the capacity of a cell ? Define ampere-hour. Explain its meanig. (iv) What is the emf of a lead accumulator ? Is it the same for large and small cells ? In what characteristic does a large cell differ from a small one ? (v) What changes go on within the cell at discharge and at charge ? Can you say how the cell gives rise to an electric current ?

(For answers, consult sections 8-5 and 8-6.)

How to charge a battery of accumulators. To charge a number of accumulators they are first connected together in series. The poles of the battery are then connected to similar poles of the mains or the charging dynamo through an ammeter and a rheostat (Fig. 8.36). The rheostat must be capable of bearing the charging current without much heating. A lamp board may be used instead (Fig. 8.37). The rheostat or the number of lamps

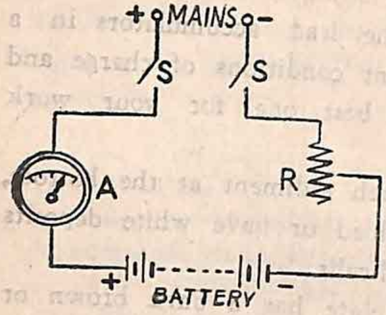


Fig. 8.36

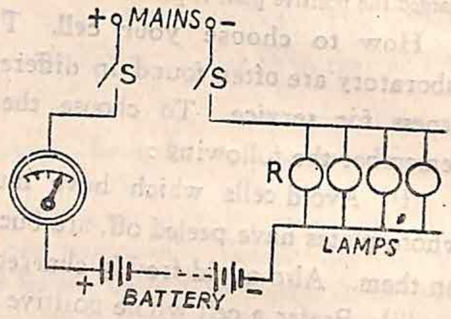


Fig. 8.37

is then adjusted so that the necessary charging current (specified by the makers) passes through the cells.

Completion of charge may be judged from the following :

(1) The specific gravity of the acid rises to the value specified by the makers (about 1·24).

(2) The plates gas freely. This is due to electrolysis of water which follows when all the lead sulphate has been converted.

It may be worth while to consider the following numerical problem in this connection. Suppose 8 cells, each of emf 1·9 volts and resistance 0·03 ohm, are to be charged by a current of 4 amps from 220 volt mains through connecting wires whose resistance is 0·1 ohm.

The cells are first connected in series and the positive end connected to the positive of the mains. The two ends should not be directly conneeted across the mains as it would cause an enormous current to flow. The 8 cells have an emf of $8 \times 1{\cdot}9 = 15{\cdot}2$ volts, which opposes the p.d. of the mains. The balance, $220 - 15{\cdot}2 = 204{\cdot}8$ volts, is available for driving current through $8 \times 0{\cdot}03 + 0{\cdot}1 = 0{\cdot}34$ ohm. The current would then be $204{\cdot}8/0{\cdot}34 = 602$ amperes nearly. Before this value is reached the fuse in the circuit will blow out.

To keep the current through the cells to 4 amperes, an additional resistance is included in the circuit. Its value R may be easily calculated :

$$4 = \frac{220 - 15{\cdot}2}{R + 0{\cdot}34} \text{ whence } R = 51 \text{ ohms nearly.}$$

8·6.2. The nickel-iron-alkali cell or Edison cell

In this accumulator, invented by Thomas Alva Edison, the electrolyte is a 21% solution of KOH in distilled water and contain a little LiOH. Hence the name 'alkali cell'. When charged, the positive plate is formed of some higher oxides and hydroxides of nickel contained in a perforated nickel-steel frame. The negative electrode consists of a mixture of finely divided Fe and FeO contained in a similar frame (Fig. 8.38). During discharge, the nickel is reduced to a lower oxide while iron is oxidised to FeO, both oxides being hydrated. The actual chemical changes during charge or discharge are not completely understood.

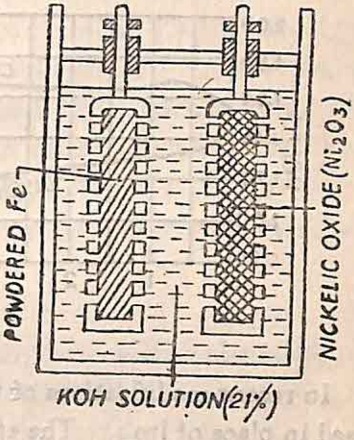


Fig. 8.38

The suggested chemical reaction within the cell may be represented as follows :

$$Fe+2Ni(OH)_3 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} Fe(OH)_2+2Ni(OH)_2$$

Unlike the lead accumulator, the electrolyte in the alkali cell undergoes no change during charge or discharge.

During discharge the emf falls off from an initial value of 1·4 volts, the mean value being 1·2. When the emf reaches 1·1 volts, no discharge should be taken from it. The charging voltage is higher and is a little over 1·6 on the average (Fig. 8.39).

The alkali cell is lighter than the lead cell and has a larger capacity per unit weight. It has several advantages over the other : the alkali cell is fairly indfferent to violent mechanical treatment, to overcharging and to discharging above the normal rate. It is not spoilt by accidental reverse charging and does not deteriorate on standing or after long use.

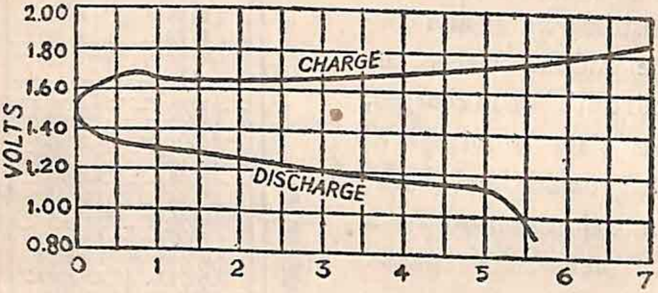


Fig. 8.39

In recent modifications of the cell, zinc and cadmium have been used in place of iron. The efficiency is higher in them.

8·7. The standard cell The standard cell is a primary cell and is used for providing a standard for measuring differences of potential. It should not be used as a source of current and should not be permitted to deliver a current of, say more than 10^{-4} ampere. To make sure of it a resistance of the order of 10^4 ohms is connected in series with the cell and incorporated in the base of the cover enclosing the cell.

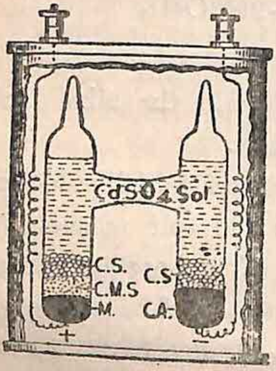


Fig. 8.40

There are two types of standard cells, one due to Clark and the other due to Weston, the latter being more commonly used. In the *Weston standard cell* (also clled the *cadmium standard cell* or the *Weston cadmium cell*) the electrodes are placed in the opposite sides of an H-shaped glass vessel (Fig. 8.40) which serves as the container for the electrolyte. The positive electrode (M) is of pure mercury, on the top of which lies a layer (C. M. S.) of mercurous sulphate in the form of a paste. It serves as the

the depolariser. The negative electrode (C. A.) is an amalgam of mercury and cadmium (90Hg+10Cd). The electrolyte is a solution of cadmium sulphate which is kept saturated by crystals of cadmium sulphate (C. S.) in both limbs. The constituents are held in place by inert packing and porous porcelain retainers. Connections to the electrodes are made by platinum wires sealed through glass. The container is hermetically sealed and is enclosed in a light-tight cover (the cell is sensitive to light). Its emf is 1·01830 volts at 20°C and varies with temperature according to the relation

$$E_t = 1{\cdot}01830 - 0{\cdot}0000406(t-20) \text{ volts.}$$

[Note that the volt is defined by international agreement as 1/1·0183 fraction of the emf of a Weston cell at 20°C.]

The arrangement in the Weston cell may be represented as

$$\mathrm{Hg} \mid \mathrm{Hg_2SO_4} \cdots \mathrm{CdSO_4} \mid \mathrm{Cd}$$

In the Clark cell the arrangement is

$$\mathrm{Hg} \mid \mathrm{Hg_2SO_4} \cdots \mathrm{ZnSO_4} \mid \mathrm{Zn}$$

Its emf is 1·433 volts at 15°C, and the variation of emf with temperature is given by

$$E = 1{\cdot}433 - 0\,0012(t-15) \text{ volts.}$$

CHAPTER 9 | ELECTRICAL MEASUREMENTS

9-1. General instructions for electrical experiments

1. All electrical contacts must be clean and tight. To ensure it, clean with sand-paper the ends of each piece of wire to be used in making the connections. After screwing down the head of a terminal gently pull at the wire and see that it does not come out.

2. Let your working table wear a neat look. Where possible, thin connecting wires should be wound into a spiral on your pencil and then used. This gives the arrangement a pleasant look, ensures better insulation, avoids short circuiting between two pieces of connecting wire and enables the circuit to be easily traced.

3. Galvanometers must always be protected against damage by accidental heavy currents. This is best done by putting a high resistance in series with the galvanometer.

For galvanometers of figure of merit 10^{-8} amp/div use 5000 ohms or higher. For a lower figure of marit, as in the case of a unipivot galvanometer, the series resistance may be 500 ohms or less.

Such a series resistance, of course, reduces the sensitivity of the galvanometer. When full sensitivity is required the series resistance has to be cut out, which is most conveniently done by plugging in the resistance.

4. Storage cells must not be short-circuited, nor should currents be drawn from them which are in excess of the maximum discharge rate of the cell. In case a large current is required, a storage cell of large capacity must be used. Alkali cells stand rough handling better than lead storage cells.

When the emf of a lead accumulator falls below 1·9V in *closed circuit*, it is better not to use it. For an alkali cell this value is 1·1 V.

To check whether a secondary cell has sufficient charge its voltage should be measured in closed circuit.

5. Do not keep currents flowing when not required.

6. Disconnect the cells and put out the galvanometer lamp when your work is over.

7. While using a resistance box or P. O. box make sure that all plugs in position are tight. Loose plugs and loose connections are the cause of much misery.

8. In all metre bridge and P.O. box work it is advisable to have a rheostat of at least 100 ohms in series with the cell if it is an accumulator. This affords fair protection to the apparatus used. If the resistance makes your arrangement insensitive, gradually reduce the resistance until the required sensitivity is reached.

9. Sometimes the null point changes by a relatively large amount when the current through the circuit is reversed. This is due to the presence of a thermo-emf in the circuit which acts in one direction. When it occurs, close the galvanometer circuit but keep the battery circuit open. You will find that the spot of light on the scale moves to a new position. Take this new position as the zero position of the galvanometer when looking for a null point (direct or reverse).

This new zero is liable to change and requires periodic checking.

9-2. To determine the figure of merit of a galvanometer

Theory. The *figure of merit* of a galvanometer is defined as the current in amperes which produces a deflection of one millimetre on a scale placed normal to the beam at a distance of one metre from the galvanometer mirror.

In the arrangement as shown in Fig. 9.1, if the circuit be closed, the current I_g flowing through the galvanometer is given by

$$I_g=\frac{S}{S+G}\cdot\frac{E}{R+\frac{SG}{S+G}}=\frac{ES}{R(S+G)+SG}$$

where R, S and G are the series, shunt and the galvanometer resistances respectively and E, the emf of the cell.

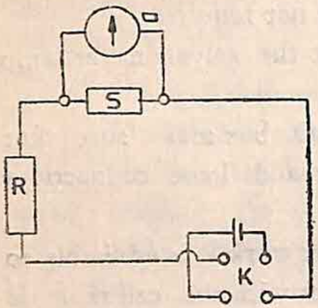


Fig. 9.1.

If this current I_g flowing through the galvanometer produces a deflection of d millimetres on a scale placed normal to the beam at a distance of D centimetres, then the deflection N millimetres which would have been produced if the scale were placed at a distance of one metre from the mirror, is given by

$$N=100d/D$$

The figure of merit F of the galvanometer, by definition, is then given by

$$F=\frac{I_g}{N}=\frac{D}{100d}\cdot\frac{ES}{R(S+G)+SG}=\frac{D}{100d}\cdot\frac{ES}{R(S+G)} \tag{9·21}$$

since SG is very small compared to $R(S+G)$.

Thus knowing R, S, G and E and measuring d and D, the figure of merit F of the galvanometer may be determined.

List of apparatus. (1) Experimental galvanometer (G) (Fig 9.1) ; (2) Resistance box (S) of 1 to 40 ohms to be used as shunt ; (3) High resistance box (R) containing 10,000 ohms or more ; (4) commutator ; (5) cell and (6) some connecting wires.

Instructions. 1. Connect as shown in Fig. 9.1. Insert a high resistance of the order of 10,000 ohms (if the galvanometer be very sensitive) or less from the resistance box (R).

2. With all the plugs closed in the shunt box, *i.e.*, with zero shunt resistance close the circuit by plugging in the commutator plugs. As all the current flows through the shunt, there will be no deflection of the galvanometer. If there is a deflection tighten all the plugs of the shunt box until the deflection reduces to zero.

3. Next, beginning from the lowest, go on increasing the shunt resistance until a deflection of 8 to 12 centimetres is produced

on the scale. Record the deflection for both direct and reversed currents.

(If you are given a table galvanometer, use current to deflect the needle by, say, 10-15 scale divisions. In this case, *the figure of merit is the current required to produce a deflection of 1 division of the scale.*)

4. Repeat the experiment using at least three different values of series resistance and for each series resistance observe deflections for at least two different shunt resistances.

5. Measure the scale-to-mirror distance D.

Experimental results :

Resistance of the given galvanometer $(G)=\cdots$ohms

Emf of the given cell=······volts.

Distance of the galvanometer mirror from the scale $(D)=\cdots$cm

No. of obs.	Series resistance R in ohm	Shunt resistance S in ohm	Deflection d in mm at D cm from the mirror		Mean d in mm	N in mm	F in amp/div
			Direct	Reversed			
1.							
2.							
2.							
4.							
5.							
6.							

Mean $F=$······amp/div.

∴ The figure of merit of the given galvanometer=······amp/div.

Precautions.

(i) With the circuit closed, the series resistace R should never be made zero as this will damage the galvanometer.

(ii) The scale should be placed such that it is normal to the beam when no current is sent through the galvonometer.

Method followed. (A brief statement)

1. The circuit was built as shown in the circuit diagram. A high resistance was put in series with the cell.

2. The shunt resistance was reduced to zero. The battery circuit was closed to check that there was no deflection of the galvanometer.

3. The shunt resistance was gradually increased from the lowest value until a deflection of about 10 cm was produced on a scale about 1m from the galvanometer. Deflections for both direct and reverse currents were noted.

4. The current was slightly altered, and each time the deflections on reversal noted.

5. The distance of the scale from the galvanometer mirror was measured.

6. The result was calculated from the data obtained.

[For table galvanometers, modify the table and this statement properly.]

Note. A D'Arsonval galvanometer has a figure of merit of the order of 10^{-7} A/div. Table galvanometers may have values of about $2-10$ μA/div.

Oral questions

1. What is figure of merit of a galvanometer ?

2. On what factors does it depend ? Will it change if the number of turns of the galvanometer coil or the cross-section or the wire used in it be altered? If so, how ?

3. Of two galvanometers, one has a larger figure of merit than the other. Which is the more sensitive ?

4. What is the purpose of the shunt in this experiment ?

5. Why should R be large ?

6. Why do you reverse the current ?

Answers. 1. See 'Theory' and the matter in brackets under item 3 of 'Instructions'.

2. It depends on the strength of the magnetic field, the area of a turn and the number of turns, and increases as they increase. It will not apparently alter if the cross-section of the wire changes, provided other factors remain the same. But Eq. 9-2.1 shows that F incrseases if G diminishes. Thicker wires give the coil a lower resistance. Hence other factors remaininig unchanged, coils of thicker wire will increase F.

3. The one which requires less current per division of deflection is the more sensitive.

4. To reduce the current through the galvanometer without using a very high resistance in series.

5. To reduce the value of the current in the circuit. The galvanometer requires a very small current.

6. To eliminate the effect of any thermal emf in the circuit.

9-3. To measure the resistance of a galvanometer by half deflection method

Theory. In the arrangement as shown in Fig. 9.2, the equivalent resistance of the shunted galvanometer equals $\frac{S(G+r)}{S+G+r}$ where S is the shunt resistance, G is the resistance of the galvanometer and r, the resistance in series with the galvanometer.

If G is very large compared to S, then whatever be the value of r, the equivalent resistance equals S.

Thus the potential drop V across S remains sensibly constant for all values of r, provided G is large compared with S.

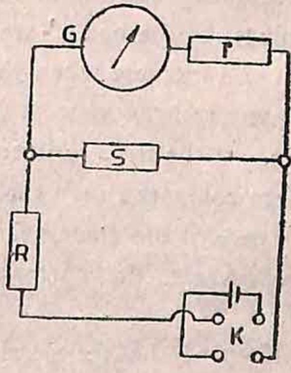


Fig. 9.2

Therefore if $r=0$, the current I_g, through the galvanometer is given by

$$I_g=V/G=Kd \tag{9-3.1}$$

where d is the deflection of the galvanometer and K is a constant of proportionality. If a resistance r is now introduced in the galvanometer circuit so as to halve the deflection d then we have

$$\frac{v}{G+r}=K\frac{d}{2} \qquad (9\text{-}3.2)$$

From equations 9-3.1 and 9-3.2, we have

$$\frac{v}{2G}=\frac{v}{G+r}$$

or

$$G=r.$$

Thus measuring the resistance r required to halve the deflection, G may be determined.

List of apparatus. (1) Experimental galvanometer (G ; Fig 9.2) ; (2) Low resistance box (S) containing fractional ohm, to be used as shunt ; (3) Resistance box (R) containing 1000 ohms or more ; (4) Resistance box (r) of 1 to 1000 ohms or more as necessary ; (5) Commutator ; (6) Cell and (7) Connecting wires.

Instructions. 1. Connect as shown in Fig. 9.2. Insert a series resistance R of the order of 1000 ohms or more and beginning from a low resistance of about 1 ohm, adjust the shunt resistance S so as to obtain a deflection of 10 to 12 centimetres on the scale. Before recording the deflection, satisfy yourself by checking that all the plugs in the box 'r' are tight. If a plug in 'r' is loose, the deflection will increase when you tighten it.

2. Insert resistances from the box 'r' so as to halve the original deflection. If the total resistance r so introduced from the box be fairly large compared with the shunt resistance S then r measures the resistance of the given galvanometer.

Now reverse the current and proceeding as before determine G.

3. Keeping the series resistance R the same, use a different shunt resistance S to obtain a different deflection and find G in a similar manner.

Change the series resistance R to some lower or higher value and find G as before.

4. In this way take readings using at least three different series resistances and for each series resistance determine G at least

for two different shunt resistances. Record your data as follows :

Experimental results ;

Emf of the battery (E)=··· volts.

Distance of the galvanometer mirror from the scale (D)=···cm.

(The numerical values in the table are fictitious and illustrative.)

No. of obs.	Current.	Series resistance in the battery circuit (R) in ohm.	Shunt resistance (S) in ohm	Resistance in the gal. circuit (r) in ohm	Gal. deflection in cm.	Gal. resistance (G) in ohm	Mean G in ohm.
1.	Direct	840	0·1	0	12·4		
		840	0·1	110 100 92 91 90 89 88	7·6 7·0 6·3 6·2 6·2 6·2 6·1	90	
	Reverse	840	0·1	0	12.2		
		840	0·1	90 91 92 93 94	6·2 6·1 6·1 6·1 6·0	92	
etc.							

Note. You will probably find that for several consecutive values of r the deflection is practically half that when r was zero. In the table record all these values and take their mean as the value of G.

Calculations :

The galvanometer current required to produce a scale deflection of 1 mm when there is no resistance in series with galvanometer.

from observation (1) we have,

(i) $\frac{I_g}{N}=\frac{D}{100\,d}\cdot\frac{ES}{R(S+G)}=\ldots\ldots$

(See Sec. 9-2 equ. 9-2.1).

(ii) etc.

Precautions. See sec. 9-2 (Previous experiment).

Method followed. (A brief statement)

1. A circuit was built as shown in the diagram. Seeking to get a scale deflection of about 10 − 12 cm, I put···ohms in the resistance box marked R and···ohms in S, after some trial. On reversal of current the deflection had the same value.

(If a *table galvanmeter* is given, 'write deflection of about 20 scale divisions' for 'deflection of about 10 − 12 cm'.)

2. A value of the resistance in the box marked 'r' was found which reduced the deflection to half the previous value. Other values of resistance in this box which gave practically the same deflection were also noted. The mean of these values is the galvanometer resistance sought.

3. Operation 2 was repeated for another value of *S*.

4. Operations 2 and 3 were repeated for other values of *R* and *S*.

Oral questions

1. Is this method applicable for determination of the galvanometer resistance in all cases ? If not, when does it fail ?

2. Will there be any error if a large deflection is taken ?

3. If the resistance of the galvanometer be low, what method would you follow for its determination ?

4. Will this method be applicable if the pole faces of the galvanometer are plane ?

5. For given values of R and S can you say what is the approximate p.d. between the galvanometer terminals ?

Answers. 1. The working equation assumes that the galvanometer resistance is very large compared with its shunt resistance. So the method will not be suitable for low resistance galvanometers.

2. The angular deflection θ of the galvanometer has to be halved. The linear deflection is proportional to θ. Up to about 10°, θ and tan θ are proportional to

within about 1%. Since no higher accuracy is aimed at, we may use deflections about 0·15 times the scale distance. The scale distances approximately 80 cm.

In the case of table galvanometers, we may use any deflection within at least $\frac{2}{3}$ of the maximum. This value is θ itself.

3. We may find it by using a metre bridge. The bridge will measure the resistance in the usual way, using another galvanometer. The current in the galvanometer under investigation must however be small. A larger current may damage the galvanometer.

4. No. In that case deflection is not proportional to the current.

5. It is approximately the battery current I multiplied by the shunt resistance S. If E is the battery voltage, the voltage V is about $(E/R).S$.

9-4. To determine the reduction factor of a tangent galvanometer by the copper voltameter method

Theory. When a current I flows through an adjusted tangent galvanometer, I is given by

$$I=K\tan\theta \qquad (9\text{-}4.1)$$

where θ is the deflection of the galvanometer produced and K, a constant of proportionality called the *reduction factor* of the tangent galvanometer. K is measured in the same unit in which I is measured.

Let the current I, measured in *amperes*, be allowed to pass through a copper voltameter. Then the amount (W) of copper deposited on the cathode is given by

$$W=Izt \qquad (9\text{-}4.2)$$

where z is the electro-chemical equivalent of copper expressed in grams per coulomb and t is the time in seconds during which the current is allowed to flow. Therefore from 9-4.1 and 9-4.2 we have

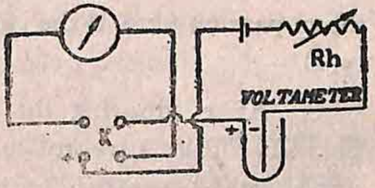


Fig. 9.3

$$K=\frac{W}{zt\tan\theta}\ \text{amps.} \qquad (9\text{-}4.3)$$

If it is required to express K in electro-magnetic units, then

$$K=\frac{W}{10\ zt\ \tan\theta}\ \text{e.m.u.} \tag{9-4.4}$$

Thus measuring W, t and θ, K may be determined either in amps from Eq. 9-4.3 or in e.m.u. from Eq. 9-4.4

List of apparatus. (1) Tangent galvanometer (T. G. ; Fig. 9.3), (2) copper voltameter, (3) suitable rheostat (Rh), ordinarily 30 to 40 ohms maximum resistance, (4) commutator, (5) storage cell, (6) stop-watch, (7) balance, (8) weight box, and (9) some connecting wires.

Instructions. 1. Level the galvanometer by means of a spirit level. This may be done in the usual way. Place the spirit level on the top glass cover along a line parallel to the line joining two of the levelling screws and bring the bubble at the centre by adjusting any one of the two screws. Place the spirit level at right angles to its previous direction and again bring the bubble at the centre by adjusting the third screw.

2. When the galvanometer is levelled, the needle will freely oscillate. Rotate the coil until its plane lies in the magnetic meridian. This happens when the pointer of the magnetic needle reads $0-0$ on the circular scale (provided there is no torsion in the suspension fibre, if the galvanometer is of the suspended needle type).

3. After adjusting the galvanometer, connect as shown in Fig. 9.3. Take care to connect the cathode plate of the voltameter to the negative terminal of the cell, so that current may flow through the voltameter from the anode to the cathode. The copper sulphate solution should be freshly prepared, if possible, and have a little sulphuric acid (about 1%) added to it. The quantity of solution taken should be such that the entire cathode plate excluding its short handle may remain immersed in it. At this stage use a dummy cathode.

4. Close the circuit and adjust the rheostat Rh until a deflection of 45° is produced. Reverse the current. The deflection will practically remain the same for a pivoted needle. [But in the case of a suspended needle the deflection may be different due to torsion in the suspension. In that case rotate the torsion head towards the side of smaller deflection till the needle moves through a distance equal to half the difference of the deflections. Then stop the current and adjust the coils so that the pointer reads 0 – 0. Pass direct and reversed currents again. If the deflections are still unequal, repeat the above operation till they are practically so.)

5. After adjusting the current for a deflection of 45° on both sides, open the circuit and remove the dummy cathode. Take the cathode plate to be used, place it on a clean piece of paper and carefully clean both surfaces of the plate by rubbing with fine grained sand paper. The purpose is to get a clean surface free from grease, on which the deposit will be uniform. So, do not touch the cleaned surfaces with your fingers, nor bring them in contact with the table. Remove the loose granules from the surface by brushing with a clean swab of cotton. The plate may then be washed by a jet of distilled water from a wash-bottle and finally dried in a stream of *cold* air.

6. Weigh the plate carefully by using a rider.

7. Insert the plate in the voltameter. See that the anode and cathode are practically parallel. Now close the circuit and start the stop-watch simultaneously.

Reverse the current every five minutes through the *galvanometer alone.* Note the deflection when the needle is steady. Since the reversals should be quickly made, prefer a Pohl commutator.

Allow the current to flow half an hour or more. Then stop the current and the watch simultaneously. Remove the cathode taking care that it does not brush against anything hard. Wash it carefully with distilled water. Dry and weigh it as before. Do not use hot air for drying as it may oxidise the deposit.

Experimental results :

Mass of copper deposit :

Weight of the copper plate		Weight of copper deposit $W=W_2-W_1$
before deposition (W_1)	after deposition (W_2)	
(…+…+…) g +(…+…+…) mg =…g	(…+—+…+…)g +(…+…+…)mg =…g	(…) g

Electro-chemical eqivalent of copper $(z)=0{\cdot}000329$ g/c.

Time-deflection record.

Time	Deflection				Mean θ
	Direct		Reversed		
	end I	end II	end I	end II	
0- 5 min	…	…			
5-10 min			…	…	
10-15 min	…	…			
15-20 min			…	…	…
etc.					

Time during which the current was allowed to flow (t)=… min
=… Seconds.

Calculations.

$$\therefore \quad K=\frac{W}{zt\tan\theta}=\text{……A},$$

$$\text{or} \quad K=\frac{W}{10\,zt\tan\theta}=\text{……e.m.u. of current.}$$

Precautions.

(i) The plane of the coil must be in the magnetic meridian. This is assured if the deflections on two sides are the same when the current is reversed.

(ii) Parallax should be avoided in reading deflections. A mirror is placed below the needle to help avoiding parallax.

(iii) The instrument should be levelled.

(iv) Error due to eccentricity of the needle should be minimised by reading both ends of the pointer.

(v) The cathode surface must be free from grease or any other non-conducting coating.

(vi) Care must be taken to ensure that no part of the deposit is removed nor oxidised before the second weighing is completed.

(vii) Careful and accurate weighing is necessary as the amount of deposit is small (generally about 50 mg).

(viii) Make sure that the cathode has been connected to the negative of the battery. It must not be in contact with the anode when inside the voltameter.

(ix) There should be no magnet or magnetic material near the galvanometer, nor any strong electric current.

Note. 1. When the deflection is 45°, the relative error in the final value due to a given error in reading the angle is a minimum.

2. Copper sulphate solution of density 1·15 to 1·18 containing 1 cm^3 of strong sulphuric acid and 1 cm^3 of ethyl alcohol per 100 cm^3 of the solution will give a good deposit and reduce risk of oxidation. A freshly prepared solution is much better than an old one.

3. Reversal of current every 5 minutes, though recommended by many teachers, does not seem to have any special value. Besides, this cannot be done quickly enough without a Pohl commutator. These commutators are not supplied to students for fear of loss of mercury.

So it seems better not to reverse. But readings should be taken every 5 minutes to see if the current is steady.

Method followed (A brief statement)

1. The galvanometer was levelled and the plane of the coil was turned so as to be in the magnetic meridian.

2. The circuit was built as shown in the circuit diagram. A dummy cathode (similar to the one to be finally used) was connected to the negative of the battery. Care was taken to see that there was no magnet or magnetic material near the galvanometer.

3. The current was adjusted to produce a deflection of about 45°. Effect of any eccentricity in the mounting of the needle was minimized by slight rotation of the coil, and reading both ends of the pointer. When properly adjusted, the deflections on both sides of the coil were practically the same.

4. The cathode plate to be used was cleaned, washed, dried and weighed carefully to the nearest milligram. The dummy cathode was then replaced by this cathode. The current and stopwatch were simultaneously started.

5. The current through the galvanometer alone was quickly reversed every five minutes, and both pointers read.

6. The current was allowed to flow for about half an hour. The cathode was carefully removed, washed, dried and weighed.

7. From the data obtained, the result was calculted.

Oral questsons

1. What is the reduction factor of a tangent galvanometer ?
2. What are the two types of tangent galvanometers that are used in the laboratory ? Which of them is better and why ?
3. What are the essential requirements of a Helmhotz galvanometer ?
4. Will you be able to work with the instrument in an iron chamber ? If not, why ?
5. Why do you adjust current to produce 45° deflection ?
6. What type of solution do you prefer for your work and why ?
7. What is meant by polarisation ?
8. Is there any polarisation e. m. f. acting within the voltameter ?
9. Why do you calculate current from the gain in weight of the cathode and not from the loss in weight of the anode ?
10. Why do you add sulphuric acid to the copper sulphate solution ?
11. Explain, why a very strong or a very weak current is not desirable.
12. Does the amount of deposit depend on the strength of the solution ?

Answers. 1. See 'Theory'. It is the constant (in current units) by which the tan θ value of the galvanometer deflection must be multiplied to get the current flowing through the galvanometer.

2. The single coil and the double-coil (Helmhotz) galvanometers. The latter is better, because the needle moves in a more uniform magnetic field.

3. Two identical parallel coaxial coils separated by a distance equal to the common radius. The needle should be centrally placed on the common axis.

4. No. The iron chamber will shut out the earth's magnetic field, and there will be no restoring couple due to the earth's field on the needle.

5. An error in reading the deflection produces minimum error in the result when the deflection is 45°.

6. Strong copper sulphate solution. It is stable and has a low resistivity. Besides, it does not polarize the cathode, as copper deposited on copper.

7. Polarization is a change in the nature of the cathode due to deposition on it of a material other than the material of which it is made.

8. As copper is deposited on copper in this case, there is no back e. m .f in the voltameter.

9. The anode (as also the cathode) contain impurities. As the anode loses matter the impurities fall off. So, loss of weight of anode material includes the mass of the dislodged impurity. This does not happen at the cathode.

10. Their addition retards oxidation of the finely deposited granules. It also makes the deposit more uniform and hard.

11. The deflections will be small or large. Any error in reading in such a case will cause a large error in the result.

12. The current and the time of deposit remaining the same, the result is not affected by the concentration. But the solution must have good conductivity.

9-5 To determine the end corrections of a metre bridge

Theory. The small contact resistances at the ends of a metre bridge wire and errors arising from the fact that the ends of the wire may not coincide with the 0 and 100 cm marks on the metre scale, contribute to the 'end corrections' of a metre bridge. These corrections are expressed as lengths in cm of the metre bridge wire which must be algebraically added to the apparent lengths of the wire on two sides of a null point.

To find these corrections, resistances P and Q (Q should be 10 to 100 times larger than P) are placed in the two gaps of the metre bridge (ACB ; Fig. 9.4), and a balance point N found in the usual way. If l and $100-l$ are the lengths of the wire on two sides of N, and λ_1 and λ_2 are the end corrections, then

$$\frac{P}{Q}=\frac{l+\lambda_1}{(100-l)+\lambda_2} \qquad (-5.1)$$

The resistances are then interchanged and a new balance point N′ found. If L and $100-L$ are the lengths of the wire on two sides of **N′**, then

$$\frac{Q}{P}=\frac{L+\lambda_1}{(100-L)+\lambda_2} \qquad (9\text{-}5.2)$$

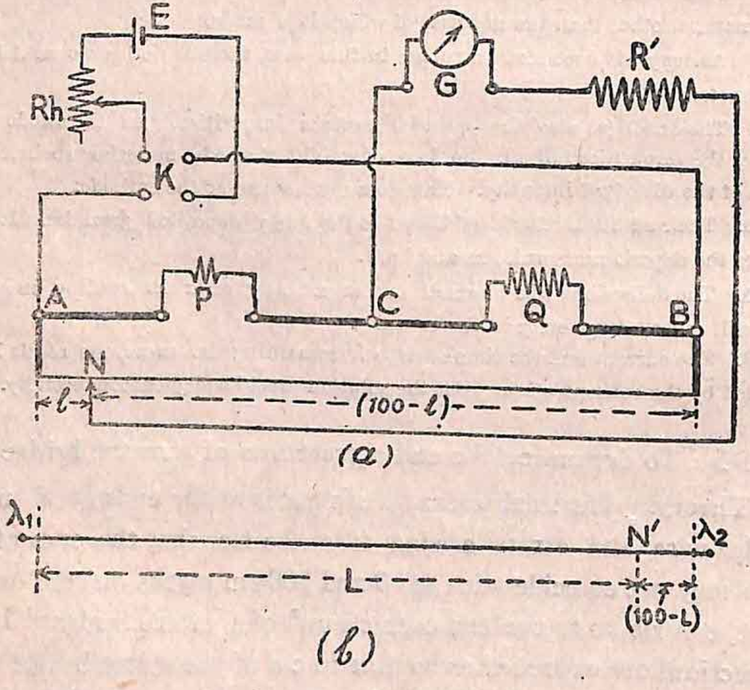


Fig. 9.4

Solving equations 9-5.1 and 9-5 2 we get,

$$\lambda_1=\frac{Ql-PL}{P-Q} \qquad (9\text{-}5.3)$$

and $$\lambda_2=\frac{Pl-QL}{P-Q}-100 \tag{9-5.4}$$

From these two equation λ_1 and λ_2 can be calculated, since P, Q, l and L are known.

Apparatus. (1) Metre bridge (AB ; Fig. 9.4) ; (2) cell (E) ; (3) rheostat (Rh) to be used in series with the cell—of resistance 100 ohms or more ; (4) commutator K for reversing current ; (5) two resistance boxes for use in the gaps—one to provide 1 ohm and the other 100 ohms ; (6) high resistance R′ of about 5,000 ohms or so for use in series with galvanometer ; (7) galvanometer (G) ; (8) connecting wires.

Instructions. Connect as shown in Fig. 9.4. Put a resistance of 1 ohm in the left gap ($P=1$) and 100 ohms in the right gap ($Q=100$). Find the balance point. Reverse the current and find the balance point again. Take l as the mean of the two values as obtained.

Interchange P and Q and proceed as above. This gives L.

Substitute the values of P, Q, l and L in equations 9-5.3 and 9-5.4 and find λ_1 and λ_2.

Next use a $P:Q$ ratio as $1:50$ and repeat.

If end correction is to be considered in a measurement, such as that described in Sec. 9-6, the lengths on two sides of a balance point should be increased by the corrections at the respective ends.

Note : If l and L are in cm, λ_1 and λ_2 will also be in cm.

End corrections are generally small. So if the balance point is near the middle of the wire the error introduced by ignoring end corrections will be small. Often this error is no bigger than the error of the other measurements.

Experimental results :

No. of obs.	Resistance in ohms in		Null Point in cm with		Mean n. p. in cm	λ_1 in cm	Mean λ_1	λ_2 in cm	Mean λ_2
	L. gap	R. gap	direct current	reverse current					
1.	P (smaller)	Q (larger)			(l)				
2.									
3.									
1.	Q (larger)	P (smaller)			(L)				
2.									
3.									

Method followed : (A short statement)

1. A circuit was built as shown in the figure.

2. With $P=1$ ohm in the left gap and $Q=10$ ohms in the right gap, null points were determined with direct and reversed currents. This was done independently thrice. The mean value of null point was used.

3. The gaps were interchanged and the above operations repeated.

4. Another ratio 1 : 20 for $P:Q$ was used, and operations 2 and 3 repeated.

5. From the equations for λ_1 and λ_2 derived from a given ratio of $P:Q$, the end corrections were calculated.

(If two different ratios P/Q were used, two sets of values of λ_1 and λ_2 will be obtained. In that case, the mean value of each (λ_1 or λ_2) should be taken as the experimental value.)

Precautions

(*i*) The minimum value of P/Q should not be less than 5, so that the null points l and L obtained by interchanging the resistances in the two gaps, differ appreciably.

(*ii*) As the end errors are quite small, the connecting wires used in the two gaps should be fairly thick and short (i. e. wires of negligible resistance) so that no further extra resistance enter in the bridge due to the connecting wires.

Oral Questions

1. Why it is called a metre bridge ?
2. What do you mean by end errors of a metre bridge ?
3. Can a metre bridge be employed for measuring a very high resistance or a very low resistance ?
4. If the wire of the metre bridge be replaced by one of different material or of different cross-Section. will the null-point change ?
5. When the bridge becomes most sensitive ?
6. If you observe the galvanometer deflections in the same direction at the two extreme ends of the wire, in spite of the correct connections, then what should be your conclusion ?

Answers. 1. Because a uniform wire of one metre long is employed and its works on the principle of wheatstone bridge. 2. See theory. 3. No. when high resistances are put in the two gaps, most of the current will flow through the bridge wire so that balance point extents over a length instead of a point, making the bridge very much insensitive. For low resistances the connecting wires and the contacts at the binding tenminals have resistances which are relatively no longer negligible and the same reason for high resistance as stated above. 4. No. the relation $P/Q=l/(100-l)$ does not depend on ρ. 5. The bridge will be most sensitive when position of the null point is near the middle of the wire *i.e.*, when the resistances of the four arms of the bridge are equal. 6. One of the resistances in the two gaps is too large in comparison to the other.

9·6 To determine the specific resistance of the material of a wire

Theory. In the arrangement as shown in Fig, 9.5, let R and X be the known and the unknown resistances respectively, and l be the distance of the null point measured from the left end A of the metre bridge. Then by the principle of Wheatstone's network, we have

$$R/X=l/(100-l)$$

or

$$X=R\times(100-l)/l \tag{9-6.1}$$

Thus knowing R and measuring l, X may be determined.

Again if X be the resistance of L centimetres of the given wire, then

$$X=\rho L/\pi r^2$$

$$\text{or} \quad \rho = X.\pi r^2/L \tag{9-6.2}$$

where ρ is the specific resistance of the material of the wire and r is the radius of cross-section of the given wire.

Thus measuring X, r and L, ρ may be determined.

List of apparatus. (1) Metre bridge (AB ; Fig. 9.5), (2) cell (E), (3) rheostat (Rh) to be used in series with the cell—of resistance 100 ohms or more, (4) commutator K for reversing current, (5) resistance box for use in the gap, preferably containing fractional ohm (say 0·1 ohm to 1 ohm or higher), (6) high resistance R' of about 5,000 ohms or so for use in series with the galvanometer, (7) galvanometer (G), (8) connecting wires, (9) the experimental wire (X), (10) screw gauge.

Instructions. Connect as shown in Fig. 9.5. Before connecting, fold 1 cm of the experimental wire at each end at right angles to the rest of the wire, and cover up to the bend within the binding screws. With 100 Ω or higher in Rh, 5000Ω or so in R$'$ and 1 Ω in R, move the sliding contact first to the left extremity and then to the right extremity of the bridge wire. If the connections have been correctly made, the deflections will be on opposite sides.

Move the contact along the wire till the galvanometer deflection is almost zero. You have got the null point approximately.

If the null point is far from the middle of the bridge wire bring it as near to the middle as you can by altering the value of R. Make the resistance in R' zero, and get the null point accurately. Reverse the current and note the null point again. If it is fairly away from the first (say, more than 4 mm), follow the method described in Sec. 9-1 (9).

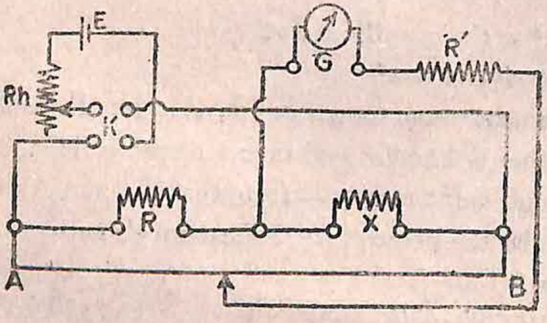


Fig. 9.5

Now interchange the positions of R and X and find the null point again. [If the value of X comes out appreciably different from that obtained from the previous measurement, an unknown resistance has been included somewhere in the bridge. This may be due to a loose or faulty contact. The source of trouble must be detected and eliminated.]

Use another value of R, the null point still lying near the middle of the bridge wire, and repeat the previous measurements. Each time you hunt for a null point, have the full value of R' in use. R' is to be reduced to zero after the approximate position of the null point has been obtained.

Altogether use at least three different values of R and take care that the null points do not move far from the middle say, not beyond 45 and 55 cm. Interchange R and X after you have noted the null points for all three values of R.

Take the mean value of X so obtained. If any one value is rather different from the rest reject it, making a note that you do so.

X is to be divided by the length of the wire between the bends that you have made at its ends and multiplied by the cross section to give the sp. resistance. The effective length is the length put across the gap, and not the total length.

Experimental results :

Distance between the bends of the wire $(l)=\cdots\cdots$cm.

Constant of the screw gauge :

Smallest main scale div.$=\cdots$mm.

$\cdots$full turns$=\cdots$mm.

Pitch of the screw gauge$=\cdots$mm.

No. of divisions on the circular scale$=\cdots\cdots$

$\therefore$ Least count$=\cdots\cdots$ mm.

Zero error$=\cdots\cdots$mm (to be added / subtracted)

Readings for the diameter of the wire (in mm) :

(a and b are at right angles.)

No. of obs.	Linear scale reading in mm	Vernier reading	Value of vernier reading in mm	Apparent diameter in mm	Mean diameter d' in mm
1 (a)					
(b)					
2 (a)					
(b)					
3 (a)					
(b)					

∴ Corrected diameter (d) = ······mm = ······cm.

Resistance of wire :

(The numerical values in the table are fictitious and illustrative.)

Resistance in ohms in		Current	Null point in cm	Mean n. p.	X (in ohms)
L. Gap	R. Gap				
1·3	X	Direct Reverse	53·3 53·3	53·3	$=1\cdot3\times\frac{100-53\cdot3}{53\cdot3}$ =
X	1·3	Direct Reverse	46·3 46·5	46·4	$=1\cdot3\times\frac{46\cdot4}{100-46\cdot4}$ =
X	1·1	Direct Reverse	50·3 50·5	50·4	=
1·1	X	etc.			

Mean $X=$······ohms.

∴ $\rho=(X/l)\times\pi d^2/4=$······ohm cm.

Note. If end corrections are to be considered increase l by λ_1 and $(100-l)$ by λ_2. λ_1 and λ_2 are the end corrections at the left and right ends respectively. These should be determined separately as in Expt. 9-5.

Precautions.

(i) The null point should not be far from the middle.

(ii) Take care that none of the plugs left in the box R is loose. This is most important.

Method followed. (A brief statement)

1. The lenth of the experimental wire between the binding screws was measured.

2. The diameter of the wire was measured at three places at right angles.

3. The resistance of the wire was measured in the usual way, with two (or three) values of the known resistance, the gaps being interchanged for each and the current reversed each time.

The data so secured was sufficient to calculate resistivity.

Oral Questions

1. Define sp. resistance. What is its unit ? How does it depend on temperature ? At what temperature have you taken your measurement ?

2. The arrangement of conductors in a metre bridge is that of Wheatstone's network. Show this clearly.

3. What is the harm if you take null points near the ends ?

Answers.

1. Specific resistance or resistivity is the resistance of a *unit cube* of the material. It is the resistance of a length of 1 cm of the material having a uniform cross-section of 1 cm^2.

Resistivity is measured in ohm. cm units in the cgs system (or ohm. m in SI units). In metals, resistivity increases with temperature. The value measured here is at the room temperature.

2. In Fig.9.4. the four arms of the Wheatstone bridge are AC, CB, AN, NB. The battery is connected between A and B (terminals of the AC, BB pair, which are also the terminals of the AD, NB pair). The galvanometer is connected between C and N (terminals of CA, AN pair and the CB, BN pair.)

3. The error will be greater, as the relative error measuring a short length is much greater than that in measuring a much longer one. Besides, an error will be introduced if there is appreciable end correction.

9-7. To determine the temperature coefficient of resistance of the material of a wire.

Theory. The temperature coefficient of resistance of the material of a wire is defined as the change in resistance per unit resistance per degree rise in temperatue.

It X_1 and X_2 be the resistances of a coil at temperatures t_1° and t_2°C respectively, then

$$X_1 = X_0 (1 + \alpha t_1) \qquad (9\text{-}7.1)$$

and $$X_2 = X_0 (1 + \alpha t_2) \qquad (9\text{-}7.2)$$

where α is the *mean temperature coefficient* between $t°_1$ and $t°_2 C$ and X_0 is the resistance of the coil at 0°C.

Eliminating X_0 from equations (9-7.1) and (9-7.2) we get,

$$\alpha = \frac{X_2 - X_1}{X_1 t_2 - X_2 t_1} \text{ per } °C \qquad (9\text{-}7.3)$$

Measuring X_1, X_2, t_2 and t_1, α may be determined.

The resistance of the coil can be measured by a metre bridge applying wheatstone Bridge Principle.

Let X be the unknown resistance in the left gap and R be the known resistance in the right gap. and l be the distance of the null point measured from the left end of the metre bridge, then

$$\frac{X}{R} = \frac{l}{100 - l}, \qquad (9\text{-}7.4)$$

from which X can be determined.

List of apparatus. Metre bridge.

Instructions. 1. Take a coil of insulated wire the temperature coefficient of whose material is to be determined. Immerse it in a test-tube containing oil and place a thermometer inside. Place the test-tube, along with the thermometer, inside a hypsometer through an opening in the cork at its top.

2. Connect as shown in Fig. 9.6 AB is the wire of the metre bridge. R is a resistance box, the resistance of which can be varied by steps of one ohm. Rh is a rheostat used in series with the cell E to limit the current drawn from it. Use a high resistance in series with the galvanometer, or a low resistance as shunt across it to control its sensitivity. Use long flexibles to connect the coil under test to the bridge.

3. Measure X_1, the resistance of the coil at the room-temperature, by means of the metre bridge, using three values of the known resistance and keeping the null point within the range 45 to 55 cm of the bridge wire. Also interchange the resistances

and take a similar set of readings. Note the temperature t_1 recorded by the thermometer.

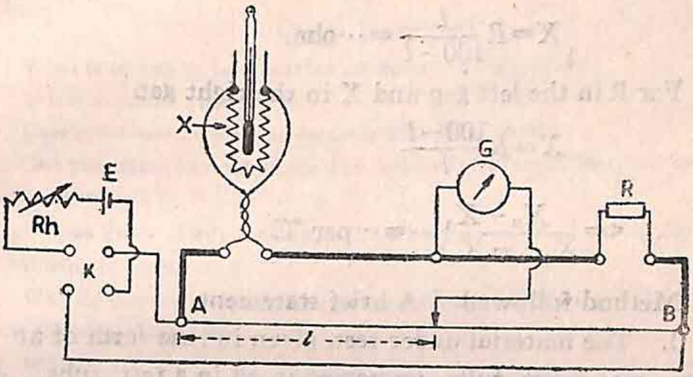


Fig. 9.6

4. Allow the water in the hypsometer to boil. Wait until the temperature of the coil reaches a maximnm value and remains stationary. Then measure X_2, the resistance at this higher temperature (t_2°C) in the same way as before.

5. Take care to protect the instruments on your table from the heat radiated by the burner. The latter may be surrounded by asbestos screens.

Experimental results :

Temperature of the coil	No. of obs.	Resistance in ohm in gap		Null point in cm with		Mean null point (l) in cm	Unknown resistance in ohm	Mean resistance in ohm
		left	right	Direct current	reverse current			
Initial (t_1) $=\cdots{}^\circ C$	1.	X_1	R_1					$\dots(X_1)$
	2.	X_1	R_2					
	3.	X_1	R_3					
	4.	R_1	X_1					
	5.	R_2	X_1					
	6.	R_3	X_1					
Final (t_2) $=\cdots{}^\circ C$	1.	X_2	R_1'					$\dots(X_2)$
	2.	X_2	R_2'					
	3.	X_2	R_3'					
	4.	R_1'	X_2					
	5.	R_2'	X_3					
	6,	R_3'	X_2					

Calculations.

For X in the left gap and R in the right gap

$$X = R\frac{l}{100-l} = \cdots \text{ohm}$$

For R in the left gap and X in the right gap

$$X = R\frac{100-l}{l}$$

$$\therefore \quad \alpha = \frac{X_2 - X_1}{X_1 t_2 - X_2 t_1} = \cdots \text{per } ^\circ\text{C}$$

Method followed. (A brief statement)

1. The material under test, given in the form of an insulated wire, was kept fully immersed in oil in a test tube. A thermometer was introduced into the oil. The ends of the coil were connected to two binding screws outside the lid covering the test tube. The test tube was placed in a hypsometer.

2. A metre bridge circuit was built up as shown in the circuit diagram. The hypsometer, with a Bunsen burner below it, was kept at a distance so as not to heat any part of the arrangement. The burner was screened off by asbestos sheets. Long flexibles wire used to connect the coil to the bridge.

3. The resistance of the coil at the room temperature was carefully determined.

4. The burner was lit and the water in the hypsometer set to boil. When the thermometer in oil continued to give a steady reading, it was noted and the resistance of the coil again determined.

5. X was calculated from the data so obtained.

Precautions.

1. In order to avoid unnecessay heating of the circuit element, the battery circuit should be closed only when making observations.

2. While heating the resistance coil, care must be taken to protect the instrument from the heat radiated by the burner.

3. The temperature of the coil at steam point should remain stationary for at least 10 minutes after which the null points should be recorded.

Oral Questions

1. What is meant by temperature coefficient of resistance ?
2. Is it a constant quantity ?
3. Does resistance increase or decrease with temperature ?
4. Can you name any substance the temperature coefficient of resistance of which is negative ?
5. Do you know of any instrument in which variation of resistance is utilised for measuring temperature ?
6. Why do you use alloys for the construction of standard resistances ? Name some of the alloys so used ?
7, Why do you reverse the current ?

Answers. 1. It is the increase in resistance per unit resistance per degree rise of temperature.

2. It changes with change in initial temperature. But for small changes of initial temperature, it is practically constant.

3. In the case of metals resistance increases with rise of temperature. In semiconductors, it decreases.

4. Graphite ; all semiconductors (such as germanium and silicon).

5. The platiuum resistance thermometer.

6. Resistance of manganin and constantan varies little with temperature. They have very small temperature coefficient of resistance. For manganin it is about $0{\cdot}1\times10^{-4}$ per °C at ordinary temperatures. For constantan, it lies between $+0{\cdot}2\times10^{-4}$ and $-0{\cdot}2\times10^{-4}$ per °C. depending on composition and past treatment.

(See the corresponding table in the appendix. For copper between 0° and 100° C α is about 43×10^{-4} per °C).

7. If there is any thermal e.m.f. in the galvanometer part of the circuit, it will disturb the true null point. The null points will be different according as this e.m.f. helps or opposes that due to the cell. The mean of the direct and reversed deflections is nearer to the true value.

(The heat radiated from the burner may create a thermal e.m.f.)

9-8. To measure the resistance per unit length of the wire of a metre bridge by Carey Foster's method

Theory. In the arrangement as shown in Fig. 9.7, *P* and *Q* are two nearly equal resistances inserted in gaps 1 and 2 respectively. Gap 3 of the bridge is closed by a copper connector S. A resistance R is introduced in gap 4 from the fractional resistance box. If now a null point be obtained at a distance l cm from the left end of the bridge wire, then by the principle of Wheatstone's bridge,

$$\frac{P}{Q}=\frac{(l+\lambda)\rho}{R+(100-l+\lambda')\rho} \qquad (9\text{·}8.1)$$

where λ and λ' are the end corrections respectively at the left and right ends of the metre bridge (represented in equivalent lengths of the bridge wire) and ρ is the resistance per unit length of bridge wire.

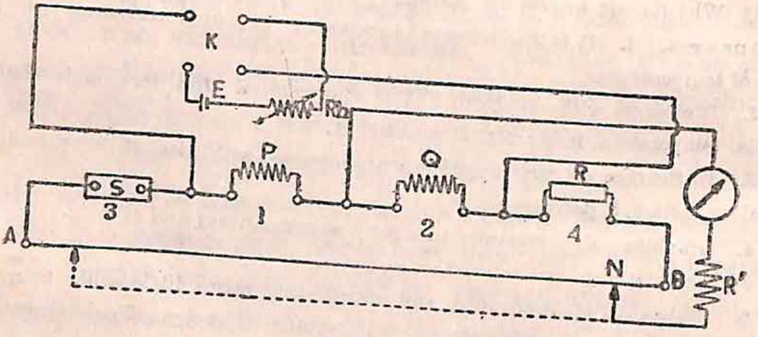


Fig. 9.7

Similarly, if the copper connector and the resistance R be interchanged and a null point obtained at l' cms from the left end of the bridge wire

$$\frac{P}{Q}=\frac{R+(l'+\lambda)\rho}{(100-l'+\lambda')\rho} \qquad (9\text{-}8.2)$$

From 9-8.1 and 9-8.2 we have

$$\frac{P+Q}{Q}=\frac{R+(100+\lambda+\lambda')\rho}{R+(100-l+\lambda')\rho} \qquad (9\text{-}8.3)$$

and

$$\frac{P+Q}{Q}=\frac{R+(100+\lambda+\lambda' \rho}{(100-l'+\lambda')\rho} \qquad (9\text{·}8.4)$$

Equating R. H. S. of equations 9-8.3 and 9-8.4 we have

$$R+(100-l+\lambda'\rho=(100-l'+\lambda')\rho$$

$$\text{or} \quad R=(l-l')\rho$$

$$\therefore \quad \rho=R/(l-l') \qquad (9\text{-}8.5)$$

Thus measuring R, l and l'. ρ may be determined.

List of apparatus. (1) Metre bridge provided with four gaps (or Carey Foster's bridge) ; (2) two nearly equal resistances (equal lengths of wire cut from the same reel may serve the purpose) ; (3) resistance box R provided with fractional ohm resistances ; (4) galvanometer ; (5) rheostat ; (6) cell ; (7) commutator and (8) connecting wires.

Instructions. 1. Connect as shown in Fig. 9.7. Use a high resistance R' in series with the galvanometer or a shunt, if the galvanometer is too sensitive. The connecting leads to R (gap 4) should be short and thick.

2. With all the plugs closed in the box R (gap 4), observe the null point ; it should be near the middle of the bridge wire. If it is not so, check your connections and the plugs of the box R for looseness.

3. Starting from the lowest resistance in the fractional resistance box R, gradually take out the plugs one after another and each time record the corresponding null point for both direct and reversed current until you reach the end of the bridge wire.

4. Interchange the copper connector and the resistance box R and in a similar manner as before record the null points for those values of R for which null points were obtained on the other side of the wire.

5. Calculate the value of ρ for the bridge wire from each set of readings thus obtained. If the bridge wire is uniform and the connecting wires of R are short and thick, the values of ρ so obtained will agree. In that case take the mean. If the values do not agree, take three of the highest values of the resistance that you used in R and calculate the mean value of ρ from them.

Experimental results :

Obs.		Resistance (ohm) in the		Null point (cm) for			$l-l'$ cm	$\rho=\frac{R}{l-l'}$ ohm/cm
		left gap	right gap	Direct	Reversed	Mean		
1.	(a)	0	R_1			(l)		
	(b)	R_1	0			(l')		
2.	(a)	0	R_2					
	(b)	R_2	0					
3.	(a)	0	R_3					
	(b)	R_3	0					
4.	(a)	0	R_4					
	(b)	R_4	0					

Mean $\rho=$ ……ohm/cm

Method followed.

1. The circuit was built as shown in the circuit diagram.

2. The resistance in gap 4 was reduced to zero by putting in all the plugs in position, each making good contact. The balance point was then found to be at……cm (near the middle).

3. Suitable fractional resistances (R) were then introduced in gap 4, gap 1 being short circuited by a copper strip. The null point was determined for each such resistance, both with direct current and reversed current. The resistances in the gaps (1 and 4) were then interchanged, and the same observation made.

This was carried on until the null points were near the ends of the wire.

4. From the data secured, ρ was calculated.

Precautions.

1. For better result, R should be so adjusted that the null-points lie within 15 cm. from the ends of the bridge.

2. To make the bridge sensitive, the value of equal resistances should preferably be equal to 1 ohm.

Oral questions

1. What are you determining ?

2. Why is it called the average value of ρ ?

3. Will it change if a metre bridge of a thicker wire but of the same material be given ?

4. Is it related in any way to the specific resistance of the material of the wire ?

5. Can you determine the specific resistance of the material of the wire if you are provided with a screw gauge ?

6. Why do you use such a resistance as would cover the greater part of wire between the null points ?

7. ρ may also be determined by measuring the total resistance of the metre bridge by a P.O. box. Which of the two methods is better and why ?

Answers. 1. The average value of the resistance per unit length of the wire of the metre bridge.

2. The value of ρ may not be the same throughout the length of the wire. Since we are finding ρ from the resistance of about the full length, it is the average value we are getting.

3. Yes. A thicker wire has a lower resistance than a thinner one of the same material.

4. Yes. It is directly proportional to the specific resistance. [The resistance R of a wire of length l, diameter d and specific resistance (resistivity) s is given by $R=s\times l/(\frac{1}{4}\pi d^2)$].

5. Yes. We have found ρ, which equals R/l. The screw gauge will give d. So we can calculate s.

6. To get a good average value for ρ.

7. The P.O. box method will give a better average since we get the average value for the whole length.

9-8.1. To determine a resistance with Carey Foster's bridge (resistance per unit length of bridge wire being known)

Theory. Let there be two equal resistances in each of the two inner gaps of a Carey Foster bridge. The unknown resistance

X is placed in the extreme left gap. A resistance box R of such range as may cover the value of X is connected across the extreme right gap.

Let a balance point be obtained at a distance l_1 cm from the left end of the wire when the resistance in the box is R. Let the balance point shift to l_2 cm from the left end when X and R interchange places. Then

$$X-R=\rho(l_2-l_1)$$

$$\text{or}\quad X=R+\rho(l_2-l_1) \qquad (9\text{-}8.6)$$

where ρ is the resistance per centimetre of the bridge wire. Hence X can be found in this way.

Changing R to $R\pm1$ (and perhaps to $R\pm2$ also) we may get new null points which will also give the value of X in the same way. We have to read $R\pm1$ or $R\pm2$, as the case may be, in Eq. 9-8.6.

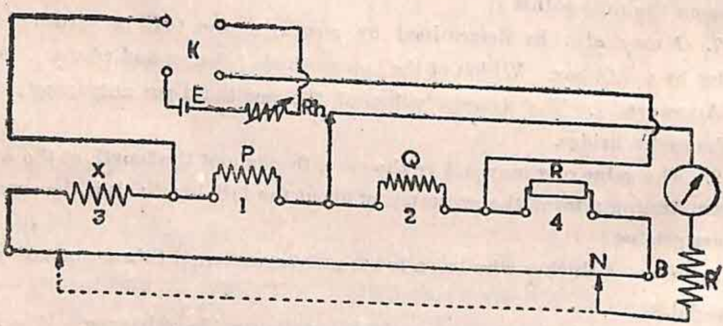


Fig. 9.8

[P,Q=two equal lengths of identical wire of resistance about one ohm each ; X=the unknown resistance ; R=resistance box of appropriate range (say 1 to 400 ohms) ; B=a cell ; K=commutator : R_1=a rheostat to control the current (about 100 ohms) , R′=series resistance to protect galvanometer (say, about 1000 ohms), G=galvanometer , N=null point.]

List of apparatus. As in Experiment No. 9-8, except that the resistance box should have a suitable range, say, 1 to 400 ohms or so. (If this range does not cover X, a box of wider range should be taken.)

Instructions. 1. Build up the circuit as shown in the circuit diagram (Fig. 9.8).

2. Short circuit X and R (the outer gaps) by thick short wires. Check if the null point is near the middle of the wire. (If it is not so, check the connections, particularly of P and Q.) Then remove the short circuit.

3. By trial, find a resistance R in the box such that the null point lies near the left end of the bridge wire. Note l_1. Interchange X and R. Find the null point l_2. In finding the null point, use both direct and reverse current.

4. Try values $R \pm 1$, $R \pm 2$ and see if you can get null points in the same way as in 3.

Record data as follows.

Experimental results.

ρ=Resistance per unit length of bridge wire=…ohm/cm.

Obs.	Resistance in the		Null point			$l_2 - l_1$	$X = R+(l_2 - l_2)\rho$
	left gap	right gap	direct	reverse	mean		
(a)	X	R	(*i*)…	…			
1.			(*ii*)…	…	…		
			(*iii*)…	…	(l_1)		
(b)	R	X	(*i*)…	…			
			(*ii*)…	…	…		
2. etc			(*iii*)…	…	(l_2)		

[Similarly for any other value of R, such $R \pm 1$ and $R \pm 2$]

(If X can be obtained for other values of R, take the mean value of X as the final result.)

Result. The unknown resistance (X)=…ohms.

Method followed.

1. The circuit was built as shown in the circuit diagram.

2. The unknown resistance X was placed in the extreme left gap and a suitable fractional resistance box was connected in the extreme right gap. Two equal resistances were connected to the inner gaps.

3. A resistance R was introduced by trial such that the null point lies near the end of the bridge wire. The null points were determined both with direct and reverse current.

4. The resistance in the box were changed to other values and null points were noted as in 3.

5. The resistances in the extreme gaps was then interchanged and the same observation made.

6. From the data secured, ρ being known, the value of the unknown resistance was calculated.

Precautions : Same as previous experiment.

Oral questions

1. Has this method any advantage over the usual metre bridge mothed of finding resistance ? If so what ?

2. In what way should the above work be modified to give ρ ?

3. What will be the harm if P and Q are not equal ?

Answers.

1. The method eliminates the effect of 'end correction' of the metre bridge. It is therefore better than the usual metre bridge methed.

2. If we use $X=0$ in the above work, we get $0=R+(l_2-l_1)\rho$ or $R=\rho(l_1-l_2)$ or $\rho=R/(l_1-l_0)$. In this case i_1 comes out to be near the right end of the wire.

3. We may not get any null point on the bridge wire.

9·9. To determine the value of a low resistance by the method of fall of potential.

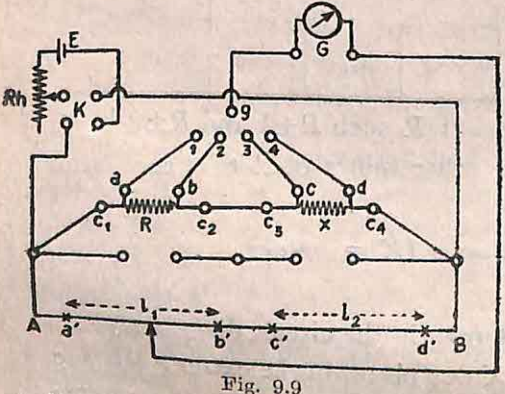


Fig. 9.9

Theory. A low resistance ab of known value R and the unknown resistance cd (of value X) are connected in series. A uniform wire AB (of metre bridge) is connected in parallel with the two and the combination is connected to a source of current as shown in Fig. 9.9.

Let the points a', b', c' and d' be equipotential with a, b, c and d respectively. If i_1 be current in the low resistance branch and i_2 that in the wire, the potential difference between a and $b = Ri_1$ and between c and $d = Xi_1$. Similarly potential difference between a' and $b' = l_1\rho i_2$; and that between c' and $d' = l_2\rho i_2$, where l_1 is the distance between a' and b', l_2 that between c' and d', and ρ is the resistance per unit length of the wire. We have then

$$Ri_1 = l_1\rho i_2 \text{ and } Xi_1 = l_2\rho i_2.$$

Dividing, $R/X = l_1/l_2$ or $X = Rl_2/l_1$.

Thus knowing R and measuring l_1 and l_2, X may be determined.

List of apparatus. (1) Standard low resistance[*] (R) of value 0·1 ohm or less, (2) unknown low resistance (X), (3) metre bridge (AB), (4) four-way key, (5) cell (E), (6) commutator (K), (7) low resistance rheostat (Rh) of thick wire, to be used in series with the cell having a value 20 ohms or less, (8) sensitive low resistance galvanometer (G ; Fig 9.9) with protective resistance.

Instructions. Connect as shown in Fig. 9.9. The connecting wires in series with the low resistances must be as short and thick as possible. The terminals of R and X are to be connected to the four-way key. If R or X or both are provided with potential

---

[*] A standard low resistance generally used in the laboratory is of the form shown in Fig. 9.10. It is a wavy strip of manganin of suitable dimensions ending in two terminals C, C called the *current terminals*. The actual resistance written on it is the resistance between two points of the strip connected to the terminals P, P, called the *potential terminals*. A standard low resistance ia generally used for measuring the drop of potential across it. The terminals C, C are connected to the circuit ; the potential leads are taken from P. P.

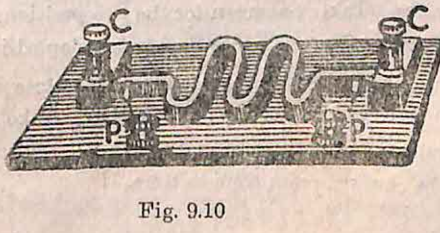


Fig. 9.10

leads, it is these leads which are to be connected to the four-way key. Connect the galvanometer in turn to the points 1, 2, 3 and 4 and find the null point for each. When finding the null point, be sure that the arrangement is sufficiently sensitive. To ensure this, shift the jockey by one milimetre on either side of the null point. If there be a readable deflection on either side of the zero, then the arrangement is sensitive. But if the null point covers a length of the bridge wire, then increase the current by reducing the resistance of the rheostat until the arrangement is sufficiently sensitive. The rheostat resistance should never be made zero, as in that case the cell and the galvanometer may be damaged. Reverse the current and find the four null points again. Interchange R and X, and take readings as before.

Repeat the experiment for three different values of the main current by varying the rheostat resistance (Rh). The readings should also be repeated by changing slightly the length of one of the connecting wires in the low resistance branch.

Calculate X separately from each set of readings and find the mean.

Experimental results :

The value of the standard low resistance $(R) = \cdots$ohm

{(d) and (r) readings for direct and reversed currents}.

[Owiug to the presence of a thermo-e.m.f. in the circuit, reversal of the current may change the position of the null point by as much as several centimetres. Taking a mean for the two positions of the null point is not proper in such cases. The procedure then to be adopted is as follows :

Break the battery circuit and then close the galvanometer circuit. The galvanometer generally shows a deflection. Take this deflected position as the zero of the galvanometer in seeking null points. This zero is unfortunately variable and should be checked from time to time.]

Length of the connecting wire	Res. in ohm in the gap		Null pts. corresponding to	Position of Null pts. in cm. for			l_1 $(b-a)$	l_2 $(d-c)$	X in ohm	Mean X in ohm
	left	right		d	r	Mean				
Short	X	R	a b c d						$X=R\frac{l_1}{l_2}$	
	R	X	a b c d						$X=R\frac{l_2}{l_1}$	
Long	X	R								
	R	X								

∴ The value of the unknown resistance (X) = ···ohm.

Precaution. Particular care should be taken to make the connecting leads Ac_1, c_2c_3 and c_4B as short and thick as possible.

If these leads are long and thin, then the total drop of potential across these leads will be much greater than the sum of the potential drops across R and X. But the drop of potential between the points A and B is the same whether we take it along the bridge wire or along the low resistance circuit. If the drop of potential across R or X is small compared to drops across the leads the lengths l_1 and l_2 will be very short. This will reduce the accuracy of the result. In order to increase the accuracy, the dead lengths. i.e. the lengths of the metre bridge wire corresponding to the drops of potential across the leads, should be reduced as far as practicable. This may be done by reducing the resistances of the connecting leads, using short thick wires.

Method followed. (A short statement)

1. The circuit was built as shown in the circuit diagram. The connecting wires for R and X which carry the battery current were made as thick and as short as possible.

2. The galvanometer was connected in turn to the four terminals (of R and X) and the balance point on the bridge wire

determined for each. Each balance point was the mean of several, obtained by independent setting and reversal of current.

3. Precaution was taken against presence of thermo-emf in the circuit.

4. The unknown value of the low resistance was calculated from the data so secured.

Oral questions

1. Is it a Wheatstone's network that you are using ?

2. Why is it necessary to use short and thick current leads in series with low resistance ?

3. Is there any harm if the wires connecting R and X be long and thin ?

4. Trace the current from the battery to the circuit and back.

5. Is the equivalent resistance between the terminals of the metre bridge greater or less than one ohm ? What is your idea of the order of magnitude of this resistance ?

6. Will there be any harm if the rheostat in series with the cell is not used ?

7. Will the positions of the null points change,

(a) if the current from the battery is increased,

(b) if the length of a connecting wire in the low resistance branch is increased ?

Answers. 1. No, we are finding equipotential points on two branches in parallel.

2. The resistance of the leads must be negligible compared with those of the low resistances. The value we get is the total resistance between the potential leads.

3. It will reduce the lengths l_1 and l_2. With a long thin wire between R and X, much of the potential drop will occur over this wire.

4. (Look at the diagram and do it. Then trace the current in the circuit.)

5. The equivalent resistance is much less than 1 ohm, since the bridge wire is shunted by a low resistance of value about $R+X$. It is of the same order as $R+X$.

6. As the bridge has a small resistance (smaller than $R+X$), a large current will pass through the cell.

7. (a) Change in battery current will not change the position of the null point unless there is much heating.

(b) Introduction of additional resistance in the low resistance branch will alter the position of the null point.

9.10. To measure a medium resistance by substitution method using a shunt box.

For measuring resistances of the order of 10^3-10^4 ohms the following approximate method, known as the *substitution method*, may be used. It is not suitable for measuring low resistances.

List of apparatus. (1) Unknown (medium) resistnce X ; (2) a resistance box R of total resistance nearly or exceeding that to be measured, (say, a box of maximum resistance 10,000 ohms) ;

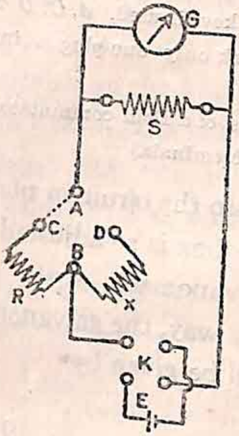


Fig. 9.11

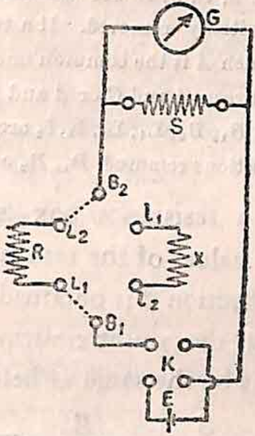


Fig. 9.12

[X=unknown resistance , R=high resistance box or divided megohm , ACD (Fig. 9.11)=two-way key , $B_1L_1L_2B_2l_1l_2$ (Fig. 9.12)=Pohl commutator with cross connections removed , K=commutator for current reversal , S=resistance in shunt box , G=galvanometer , E=cell.]

(3) shunt resistance box S containing resistances 1 to 1000 ohms ; (4) galvanometer G (preferably of high resistance) ; (5) cell ; (6) commutator K for reversing current ; (7) a two-way plug key, or a plug type commutator, or a Pohl's commutator with cross-connections removed ; (8) connecting wires.

Theory. In the arrangement shown in Fig. 9.11 (or Fig. 9.12), if the unknown resistance X is included in the circuit [by closing the gap between A and D of a two-way plug key or a plug type commutator as in Fig. 9.11, or by rolling the rider of the Pohl's commutator, to the right as in Fig 9.12], the current C flowing through the galvanometer is given by

$$C_g=\frac{S}{S+G}\cdot\frac{E}{X+\dfrac{SG}{S+G}}=Kd \qquad (9\text{-}10.1)$$

where S and G are the shunt and galvanometer resistances respectively ; E is the e.m.f of the cell ; d is the deflection of the galvanometer and K is a constant of proportionality.

(In Fig. 9.11 A, B, C, D are the terminals of a plug type commutator of which the plugs are initially removed. If a two-way plug key is used, A, C, D are its terminals of which A is the common one. During work only one plug is inserted as necessary between A and C or A and D.

In Fig 9.12 $B_1, B_2, L_1, L_2, l_1, l_2$ are the terminals of a Pohl commutator with the cross-connections removed, B_1, B_2 are the middle terminals.)

If now a resistance box is brought into the ciruit in place of X and the value of the resistances in the box is so adjusted that the same deflection d is obtained on the galvanometer scale without altering the shunt resistance S in any way, the galvanometer current must be the same as before, and will be given by

$$C_g = \frac{S}{S+G} \cdot \frac{E}{R + \dfrac{SG}{S+G}} = Kd \qquad (9\text{-}10.2)$$

Comparing 9-10.1 and 9-10.2 we find $X=R$.

Instructions. Arrange your apparatus as shown in Fig. 9.11 or 9.12. In the case of a two-way plug key or plug type commutator as shown in Fig. 9.11, use only one plug to close either the gap between A and D or between A and C to bring X or R in the circuit, as the case may be. When a Pohl's commutator, with cross-connections removed, is used as in Fig. 9.12, X or R is brought in the circuit by rolling the rocker to the right or to the left.

Put X in the circuit. With zero shunt resistance, *i. e.*, with all the plugs of the shunt resistance box closed, there should be no deflection of the galvanometer. If there is a deflection in this condition, check the plugs of the shunt resistance box for looseness.

Gradually increase the shunt resistance till a deflection of three-quarters of the scale is produced. Note this deflection.

Reverse the current and observe the deflection again. The mean of the two deflections measures *d*.

Bring the resistance box into the circuit with all its plugs pulled out. Adjust the plugs so as to produce the same mean deflection *d* as before. You may find that over a range of values of resistance in the box, the deflection practically shows no change. In such a case, take the mean of all such values as *R*.

Repeat for two other values of *d*. Take the mean of the three values of *R* so obtained. This is the value of X.

Experimental results :

No. of obs.	Resistance in series	Shunt Resistance	Deflection			*X* in ohms
			Direct	Reversed	Mean	
1	*X* *R*					
2	*X* *R*					
3	*X* *R*					

Mean X=……ohms.

∴ the unkwon high resistance=……ohms.

Note: When the deflections for *X* and *R* are slightly different, the shunt resistances remaining the same, we may take the resistance to be inversely proportional to the deflections if the resistance of the shunted galvanometer is negligible compared with *X* or *R*. In such a case, if *d* and *d'* are the deflections for *X* and *R* respectively, we shall have

$$X=Rd'/d.$$

9-11. To measure a high resistance by deflection method

For measuring a resistance of the order of 10,000 ohms or more a simple deflection method (also known as *substitution method*) as described below is used.

List of apparatus. (1) Unknown high resistance X, (2) divided megohm R, (3) shunt resistance box S containing resistances 1 to 1000 ohms, (4) galvanometer G (preferably of high resistance), (5) cell E, (6) plug type commutator or a Pohl's commutator ($B_1L_1L_2B_2l_1l_2$) with cross-connections removed and (7) connecting wires.

Theory. In the arrangement shown in Fig.s 9.11 and 9.12 if a known high resistance R is included in the circuit by closing the gap between A and C of a plug type commutator as in Fig. 9.11 [or by rolling the rider of the Pohl's commutator to the left as in Fig. 9.12], the current C_g flowing through the galvanometer is given by

$$C_g=\frac{S}{S+G}\cdot\frac{E}{R+\dfrac{SG}{S+G}}=Kd \qquad (9\text{-}1\ .1)$$

where R, S, G are the series, shunt and the galvanometer resistances respectively ; E is e.m f. of the cell ; d is the deflection of the galvanometer and K is a constant of proportionality.

Similarly, with the unknown high resistance X in the circuit, the galvanometer current C'_g is given by

$$C'_g=\frac{S'}{S'+G}\cdot\frac{E}{X+\dfrac{S'G}{S'+G}}=Kd' \qquad (9\text{-}\ 1.2)$$

where X and S' are the series and shunt resistances respectively and d', the galvanometer deflection. As X and R are very high, the resistance of the galvanometer or the equivalent resistance of the shunted galvanometer $\frac{SG}{S+G}$ or $\frac{S'G}{S'+G}$ is negligible compared to X or R. Therefore Eq.s 9-11.1 and 9-11.2 reduce to

$$C_g=\frac{ES}{R(S+G)}=Kd \qquad \ldots \qquad (9\text{-}11.3)$$

$$C'_g=\frac{ES'}{X(S'+G)}=Kd' \qquad \cdots \qquad (9.11.4)$$

Dividing Eq. 9-11.3 by Eq. 9-11.4, we have

$$\frac{XS(S'+G)}{RS'(S+G)}=\frac{d}{d'},$$

$$\text{or,} \quad X=R.\frac{S'(S+G)}{S(S'+G)}\cdot\frac{d}{d'} \qquad \cdots \qquad (9\text{-}11.5)$$

Thus knowing R, S, S' and G and measuring d and d', X may be determined.

Again if, X be very large so as to produce a measurable deflection even without the shunt S' (*i.e.* $S'=\infty$), the expression for X further redces to

$$X=R\,\frac{S+G}{S}\cdot\frac{d}{d'} \qquad \cdots \qquad (9\text{-}11.6)$$

Instructions. Arrange your apparatus as shown in Fig. 9.11 or 9.12. In the case of a plug type commutator as shown in Fig. 9.11, use only one plug to close either the gap between A and C or between A and D to bring R or X in the circuit. When a Pohl's commutator, with cross-connections removed is used as in Fig. 9-12, R or X is brought in the circuit by rolling the rocker to the left or to the right.

Put X in the circuit. With zero shunt resistance, *i. e.*, with all the plugs of the shunt resistance box closed, there should be no deflection of the galvanometer. If there is a deflectiod in this condition, check the plugs of the shunt resistance box for loosenses.

Gradually increase the shunt resistance till a deflection of 8 to 12 cms is produced on the scale. Even if using the highest resistance available in the shunt box, you find that the deflection is still too small, cut out the shunt box (*i.e.*, make $S'=\infty$), so as to drive the whole of the main current through the galvanometer. Observe the deflection. Reverse the current and observe the deflection again. The mean of the two deflections measures d'.

Put in all the plugs of the shunt box to make its resistance zero. Use a suitable known high resistance R (any value between

10,000 and 100,000 ohms), and bring it in circuit. Proceeding in a similar manner as before, adjust the shunt resistance so as to produce a mean deflection d nearly equal * to the deflection d' as observed with X in series. From the set of data thus obtained, calculate X either from relation 9-11.5 or from 9-11.6, if $S' = \infty$.

Varying S', R and S, obtain at least three sets of readings, making d and d' nearly equal in each case.

Calculate X from each set of readings.

Experimental results :

Resistance of the given galvanometer $(G) = \cdots\cdots$ohms.

Tabulate the data and calculate the result as in Sec. 9-10.

Oral questions

1. Why is a P.O. box not used for measuring the resistance in this case ?

2. Has the substitution method any advantage over the bridge method when measuring such a resistance ?

3. What is the precision you expect from the substitution method ?

Answers. 1. A P. O. box will be too insensitive when such high resistances are used.

2. The bridge method (as in a P. O. box) may be used for resistances in the approximate range $1-10^3$ ohms, or at most 10^4 ohms if the galvanometer is sensitive enough.

3. This is determined by the precision in the value of d.

9-12. To determine the value of J, the mechanical eqivalent of heat, by Joule's calorimeter

List of apparatus. (1) Joule's calorimeter ; (2) a suitable resistance for controlling the current from the mains (R' of Fig. 9.13) or a battery (r of Fig 9.14) ; (3) a plug or a switch for starting and stopping the current ; (4) voltmeter (V) ; (5) ammeter (A) ; (6) thermometer, reading to one-fifth of a degree ; (7) balance ; (8) weight box ; (9) stop-watch ; (10) a quantity of oil of known specific heat and (11) connecting wires.

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* It may be shown mathematically that even if d and d' are comparatively large but nearly equal, than also

$$\frac{d}{d'} = \frac{\tan\theta}{\tan\theta'} = \frac{\theta}{\theta'}$$

Theory. If current I flows through a resistance producing a drop of potential V across it then the work (W) done by the charge transferred in time t is given by

$$W=VIt \text{ joules}$$

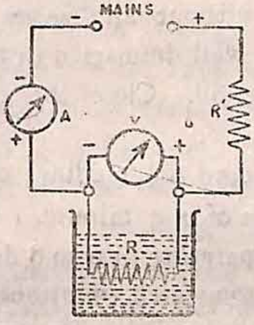


Fig. 9.13

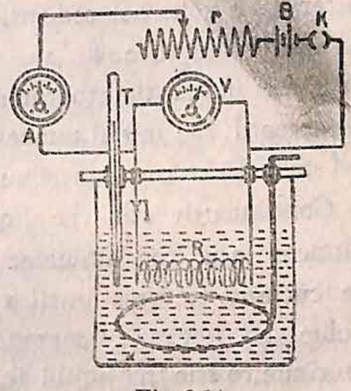


Fig. 9.14

where I and V are measured in amperes and volts and t is in seconds. This work appears as heat in the resistor.

Let the resistance coil be immersed in calorimeter of heat capacity w containing m grams of oil of specific heat s. If the whole of the heat developed (H) passes into the calorimeter, we shall have

$$H=(ms+w)\,\theta \text{ cal}$$

where θ°C is the rise in temperature of the calorimeter and its contents..

But by the principle of conservation of energy $W=JH$, where J is the mechanical equivalent of heat.

$$J=\frac{W}{H}=\frac{VIt}{(ms+w)\theta} \text{ joules per cal} \qquad \therefore \qquad (9\text{-}12\,1)$$

Thus knowing s and w and measuring other quantities on the right-hand side of 9-12.1. J may be determined.

Instructions. Weigh the calorimeter and stirrer correct to 0·1 g. Take a quantity of oil in the calorimeter so that the resistance coil may completely dip into it. Weigh the calorimeter along with the oil and stirrer.

Arrange your apparatus as shown in Fig. 9.13 or 9.14 as the case may be. Take care to connect the voltmeter V and the ammeter A in the proper way. If the value of the resistance coil R be 4 to 6 ohms (which is generally the case), adjust R' so that a current of one to two amperes may flow through R. If a battery of 6 volts be used instead of the mains, it may be directly connected to R through an ammeter A without any series resistance R'. Keep the thermometer bulb well immersed in the oil and reeord the initial temperature of the oil. Close the circuit and start the stop-watch simultaneously.

Continuously stir the liquid and record the readings of the voltmeter and the ammeter at intervals of one minute. Allow the current to pass until a rise in temperature of 6 to 8 degrees is observed. Stop the current and the stop-watch simultaneously. Continue to stir the liquid and record the maximum temperature attained by the thermometer.

Experimental results :

Mass of the calorimeter and strrer $(m_1)=\cdots$gm.

Mass of cal. +stirrer+oil $(m_2)=\cdots$gm.

$\therefore$ Mass of oil taken $(m)=m_2-m_1=\cdots$gm.

Specific heat of the given oil $(s)=\cdots$

Heat capacity of the calorimeter and stirrer $(w)=\cdots$cal

Zero error of voltmeter$=\cdots$volt (add/subtract)

Zero error of ammeter$=\cdots$amp (add/subtract)

Initial temperature of oil $(\theta_1)=\cdots$°C

Time	Voltmeter reading (V)	Ammeter reading (I)
1 min 2 min etc.		

Mean $V=\cdots$volts ; mean $I=\cdots$amp.

Mean corrected voltmeter reading $(V)=\cdots$volts.

Mean corrected ammeter reading $(I)=\cdots$amperes.

Final temperature (θ_2) of oil$=\cdots$°C

Time during which the current is passed $(t) = \cdots$ min$\cdots$secs,
$= \cdots\cdots$seconds.

Rise in temperature $(\theta) = \theta_2 - \theta_1 = \cdots\cdots$°C

$$\therefore \quad J = \frac{VIt}{(ms+w)\theta} \cdots \text{joules/cal} = \cdots \text{ergs/cal.}$$

Precautions. (i) The current through the coil should be at least 1 to 2 amperes, as otherwise the rate of rise of temperature would be too slow and a longer period will be taken to produce a given rise in temperature. But if the period is long, heat loss due to radiation etc. will increase. As this loss is not taken into account, the final result will be too high.

(ii) The usual precautions for reducing this loss should be taken.

(iii) The thermometer bulb should not touch the coil. If it touches, it would indicate a temperature higher than that of the liquid.

Cooling correction. If it is desired to correct for the loss of heat due to the cooling of the calorimeter, the oil may be initially cooled as much below the room temperature as the proposed rise. The heat gain by radiation during the first half of the rise will be compensated by the heat loss during the second half.

Oral questions

1. What is meant by the mechanical equivalent of heat? On what does it depend?

2. Where is work done in this experiment? Who does this work?

3. Define the volt and the coulomb.

4. Since work is defined as the product of a force and the distance through which its point of application moves, how would you reconcile the work done in this case with the definition?

5. What is the resistance of your heater?

6. Will the value of J that you get increase or decrease if you take the heat losses into account?

7. How do the heat losses occur? How can you take them into account?

8. Will you prefer sending a small current through the heater, or a large one? Give reasons.

9. When is J equal to unity?

Answers. 1. When an amount of work W is fully converted into heat producing H heat units, the ratio W/H is a constant quantity and is known as the mechanical equivalent of heat (or Joules equivalent). Its numerical value depends on the units in which W and H are measured.

2. Work is done when the current flows through the heating resistor. The battery does work.

3. (Say from your text book.)

4. Force × distance is *mechanical* work. Here the work done is electrical and has magnitude VIt.

5. It is the ratio V/I. (see the voltmeter and ammeter readings. V/I is the resistance of the coil.)

6. During heating, some heat is lost by radiation. The H that we measure is, therefore, less than that H' developed. W/H is the true value of J. W/H is greater than this value, since $H<H'$. So, if we take heat loss into account the value we get will decrease.

(Without correction for radiation loss, we get a rather high value for J.)

7. Heat loss occurs mainly by radiation, and some by convection and conduction, depending on the actual arrangement. A simple way is what has been stated under 'Cooling correction' above.

8. A larger current is preferred. It will produce heating, at a faster rate. Hence there will be less heat loss. For given temperature rise, as the time for the given rise will be shorter.

9. The present international practice is to measure heat in *joules* since heat is a form of energy and the SI unit of energy is the *joule*. Hence W and H are both measured in joules. This makes $J=1$.

9-13. The potentiometer and its working principle

Any arrangement with which a variable and measurable drop of potential may be obtained is called a potentiometer.

Description: The type of apparatus ordinarily used in the laboratory is shown in Fig. 9.15. It consists of an even number (generally 10) of identical, uniform wires of the same material, each one metre long and joined in series by thick copper strips at their ends. The wires run parallel to each other over an insulating glass plate mounted on a wooden (or plastic) board. The two ends of the series thus formed are brought to two terminals A and B as shown in Fig. 9.15. A triangular jockey J slides along a metre scale over the wires with two of its legs resting in a groove cut in the board parallel to the wires. Its third leg rests on a long brass strip. At the ends of this brass strip there are two terminals C and D, through any of which connection to the jockey may be established. There is a slit cut in the jockey, along

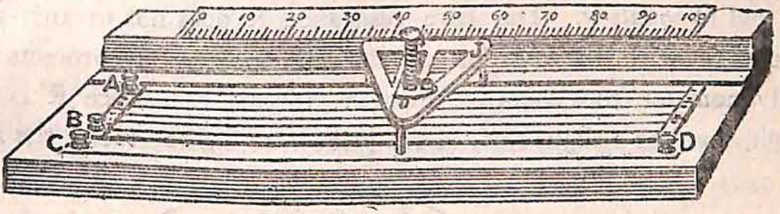


Fig. 9.15

which a knife-edge contact can be shifted to any of the potentiometer wires. Thus by sliding the jockey and shifting the knife-edge contact along the slit, any point of any of the wires may be brought into contact with the terminal C or D, while the position of the point can be read from the metre scale. In one design the jockey carries separate knife-edge contact pieces for each wire.

Working principle: If two independent potential differences, V_1 and V_2 in opposition, are connected in series through a galvanometer so as to form a closed circuit and if further no current flows through the galvanometer, then by Kirchhoff's law we have $V_1=V_2$.

When a current flows through the potentiometer, a drop of potential is produced between the terminals A and B. By moving the jockey along the wires a variable drop of potential is obtained between the terminal A and the point of contact with the jockey. In order to measure an unknown drop of potential V, the terminal A and the jockey point are connected across V in opposition through a galvanometer to form a closed circuit as shown in Fig. 9.16. By adjusting the position of the jockey. a null point may be obtained. Then the drop of potential between A and the null point N equals V.

It may be mentioned in this connection that a high resistance R'_1 as in Fig. 9.16, is used to protect the galvanometer from accidental heavy current which may flow through it during adjustment. But when a null point is obtained, *whatever be the resistance in the galvanometer circuit, the drop of potential between* A *and* N *equals* V. The series resistance R' does not in any way interfere with the position of the null point, but protects the galvanometer from damage. Further, if this resistance R' is too high, then for a slight shift of the jockey on either side of the null point, no readable deflection will be produced, as the current may be too small. The arranement, then, becomes insensitive. To provide both protection and sensitivity use a high protective resistance and find a rough value of the null point ; then cut out the protective resistance and find the null point accurately.

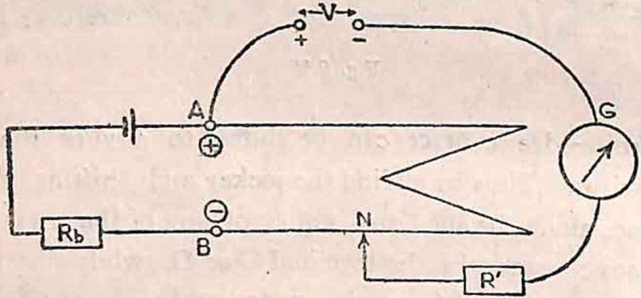


Fig. 9.16

As the potentiometer wire is uniform throughout, the drop of potential per unit length of the wire is constant. Let it be e. If l is the length of wire between A and the null point N, then

$$V = el.$$

The drop of potential per unit length of the potentiometer wire may be determined by any of the following methods :

Method I : If i is the current in amperes which flows through the potentiometer wire, R_p is the resistance of the potentiometer and n is the number of wires (each one metre long) in the potentiometer, then

$$e = \frac{iR_p}{100n} \text{ volt per cm.}$$

Knowing i, R_p and n, e may be calculated.

Method II : If we do not know the current i but know the e.m.f. E of the driver cell and the resistance R_b in series with the driver cell, then

$$i=E/(R_p+R_b) \text{ and}$$

$$e=\frac{E}{R_p+R_b}\cdot\frac{R_p}{100n}$$

Method III : e may also be determined by balancing a known potential difference V_1 across a length l_1 of the wires, In that case $e=V_1/l_1$.

From what has been said it is evident that the *drop of potential to be measured must be less than the total drop of potential between the end terminals A and B ; otherwise the method fails.*

9-14. To compare the e.m.f.s of two cells with the help of a potentiometer

Theory. If I be the current in amperes flowing through a potentiometer of length L cm and resistance R ohms, then the potential drop per cm. of the wire is IR/L volts.

Now if, the e.m.f. (E_1) of the first cell is balanced on a length l_1 of the potentiometer wire, and the e.m.f. (E_2) of the second cell is balanced on a length l_2 of the potentiometer wire,

then $E_1=\frac{IRl_1}{L}$ and $E_2=\frac{IRl_2}{L}$ whence $\frac{E_1}{E_2}=\frac{l_1}{l_2}$.

List of apparatus. (1) A potentiometer (AB ; Fig. 9.17) ; (2) a lead storage cell (E) to drive current through potentiometer ; its e.m.f. must be greater than the e.m.f. of either of the two cells (E_1, E_2) to be compared (E_1 and E_2 may be a Leclanche and a Daniell cell) ; (3) resistance in the form of rheostat (Rh) to be put in series with the potentiometer ; (4) a plug-key and a two-way key ; (5) two cells (E_1, E_2) whose e.m.f.'s are to be compared ; (6) galvanometer ; (7) high resistance R' (about 10,000 ohms) to be put in series with the galvanometer, (8) connecting wires.

Instructions. Connect as in Fig. 9.17. The positive terminals of all these cells must be connected to the same terminal A of the potentiometer. E_1 and E_2 may be connected at will to the galvanometer through a two-way key. Bring E_1 into circuit.

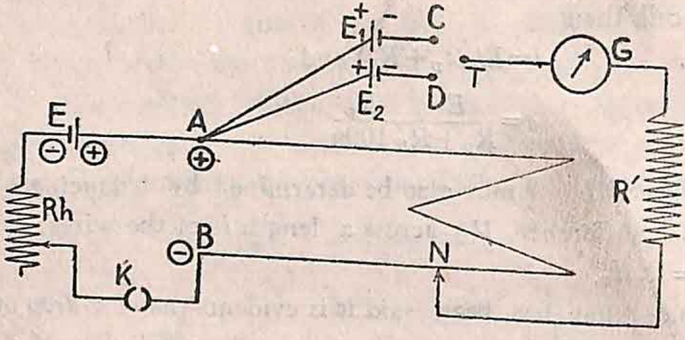


Fig. 9.17

With no resistance in Rh and maximum resistance in R' establish momentary contact with the Jockey first near one end and then near the other end of the potentiometer. If the connections have been correctly made and E is greater than E_1, the deflection in the two cases will be on opposite sides, failing which the defect must be traced and remedied. After having got deflection on opposite sides, obtain approximate null points for E_1 and E_2, thus finding which of them has higher e.m.f. keep this one in circuit and adjust the resistance of the rheostat so that a null point is obtained near the middle of the last wire. Find the approximate null point. Cut the resistance R' and secure the exact null point.

Now bring the other cell (the one of lower e.m.f) into the circuit (by changing the plug in the two-way key). Find the exact null point without making any change in Rh.

Reduce the value of the resistance in the rheostat till this null point shifts to about the middle of the next lower wire. Secure the exact null points for both the cells (E_1 and E_2) without altering this new value in Rh. Reprat the observations with a still lower value of the resistance in Rh and thus secure three sets of null points for three different values of current through the potentiometer.

Experimental results :

No. of obs.	Cell in the circuit	Null points			Total length of the pot. wire for balance in cm	$\frac{E_1}{E_2}=\frac{l_1}{l_2}$
		On wire no.	Scale reading in cm	Mean Sc. reading in cm		
1.	E_1	10th	....	......	... (l_1)	
	E_2	...			... (l_2)	
2.	E_1	9th	....	... =		
	E_2	...	....			
etc.						

Precautions. (1) The potentiometer wire must be of uniform cross-section. (2) The e.m.f. of the cells to be compared must be smaller than the e.m.f. of the driver cell. (3) The driver cell should not run down.

End error : For greater accuracy end-error is to be taken into consideration. To determine the end-error (ε) connect the two cells in series. Find a balance point corresponding to an e.m.f. (E_1+E_2). Let the balance be obtained at length l_3 from A. Let l_1 and l_2 be the corresponding balance points with E_1 and E_2 respectively.

$$\text{Then, } E_1=(\varepsilon+l_1)\frac{IR}{L},\ E_2=(\varepsilon+l_2)\frac{IR}{L}\ ;\ E_1+E_2=(\varepsilon+l_3)\frac{IR}{L}.$$

$$\therefore\ \varepsilon+l_1+\varepsilon+l_2=\varepsilon+l_3 \quad \varepsilon=l_3-l_1-l_2.$$

For this part of the experiment take E as a battery of two lead storage cells connected in series, for the e.m.f. E of the driver cell must be greater than (E_1+E_2).

Note : E.m.f of a lead storage cell is 2 volts, of a Leclanche cell 1·5 volts and of a Daniell cell about 1·08 volts With resistance in *Rh* cut out to zero value, the *p.d* between the terminals of the potentiometer is practically 2 volts. So, in this condition a Leclanche cell will be balanced on about three-fourths of the total length of wire (i.e. nearly 750 cm of wire or about the middle of the wire from *A*). The Daniell cell reach somewhere on the sixth wire. As resistance in *Rh* increases, null points shift to longer distances from *A*.

Oral questions.

1. Which is the driver cell ? What is its function ? Trace the current from the driver cell through the potentiometer back to the cell.

2. How does increasing the resistance in the rheostat alter the p. d across the potentiometer ?

3. Does a current flow through E_1 or E_2 when it is balanced ? Through the driver cell ?

4. When E_1 is balanced, consider the mesh cantaining E_1, the galvanometer and the corresponding balancing length AN of the potentiometer and apply Kirchhoff's second law to it. What do you find ? Does the resistance in series with the galvanometer affect the position of the null point ?

Answers.

1. *E* in fig . 9.17. To create a potential drop across the potentiometer wire. Show by arrow.

2. P. d. decreases.

3. No. Yes.

4. 1st part do yourself. No ; it will not affect the position of the null point. The sensitivity of the galvanometer decreases.

9·15. To measure the e. m. f. of a cell (a potentiometer of known resistance and a milliammeter being provided)

List of apparatus. (1) A potentiometer (AB ; Fig. 9.18) of known resistance ; (2) battery (E) e.m.f. of which must be greater than E′, the e.m.f. to be measured ; (3) milliammeter (*m.a.*) of range up to 100 or 150 milliamperes ; (4) resistance Rh to be put in series with the potentiometer (it may be a rheostat of value 20 ohms or so with a good sliding contact or a resistance box) ; (5)

plug key ; (6) cell (E'), e.m.f. of which is to be measured ; (7) galvanometer ; (8) high resistance R' of value 5000 to 10,000 ohms to be used in series with the galvanometer.

Theory. If i be the current in amperes flowing through a potentiometer consisting of a uniform wire of length L centimetres and resistance R_p ohms the potential drop per centimetre is iR_p/L volt.

If a cell of e.m.f. E' be balanced on a length l of the potentiometer wire, then E' is given by

$$E'=iR_pl/L \text{ volts.}$$

Instructions. Connect as shown in Fig. 9.18. The positive terminals of both E and E' are connected to the same terminal A of the potentiometer. With no resistance in Rh and maximum resistance in R' establish momentary contacts of the jockey first near one end of the potentiometer and then near the other. If the connections have been correctly made and E is greater than E', the deflections in the two cases will be on opposite sides, failing which the defect must be traced and remedied.

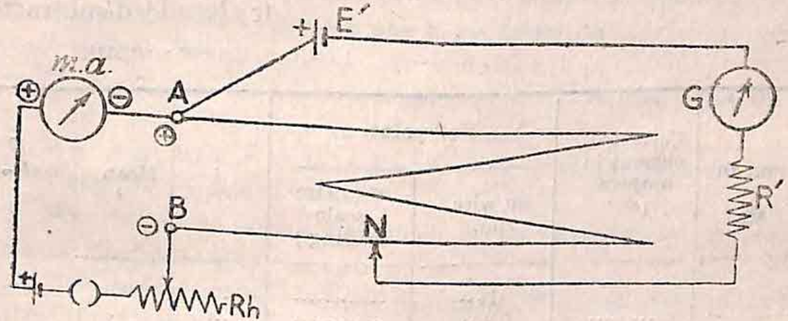


Fig. 9.18

After having got deflections on opposite sides, adjust the resistance of the rheostat so that a null point is obtained near the middle of the last wire. Find the approximate null point. Cut out the resistance R' and secure the exact null point (See Sec. 9-13). Read the corresponding value of the current in the milliammeter.

Slightly disturbing the rheostat *Rh*, reset it for the same current again and determine the null point again as before. Repeat your observations thrice for the same current.

Slightly decrease the resistance *Rh*, so as to obtain a null point on the last wire but one and repeat your observations. Do so for at least three different values of the current and for each value of current, observe null points three times for three independent settings of the rheostat *Rh*. Record as follows :

Experimental results :

Total length of the potentiometer wires $(L)=\cdots$ cm.

Total resistance of the potentiometer $(R_p)=\cdots$ ohm

Zero error of the milliammeter $=\cdots$ milliamp

(to be added/subtracted)

$=\cdots$ amp.

Current in am	Corrected current in ampere (i)	Null point		l	Mean l	$E = iR_p l/L$
		on wire no.	at (metre scale reading)			
....	....	(i)… (ii)… (iii)…	....	… … …	…	
etc.	etc.	etc.	etc.	etc.	etc.	

Mean $E' = \cdots$ volts.

∴ the e.m.f. of the given cell $=\cdots$ volts.

Note. When you get the null point with $Rh=0$, you can calculate E'. The maximum resistance which may be put in *Rh*, so as still to get a null point is $\dfrac{E-E'}{E'}R_p$. E for a lead storage cell is 2 volts approximately when fully charged. R_p for a ten wire potentiometer is about 20 ohms or so. If *Rh* is given a value higher than the above, the null point goes beyond the potentiometer. Further remember that if E is less than E', the experiment fails and a null point cannot be obtained. (See Sec. 9.13.)

[For write-up of the "Method followed", consult the last experiment (Sec. 9-14). The drop of potential per centimetre =Potentiometer resistance $R_p \times$ Current through it in amperes (as obtained from the milliammeter) divided by the total length of the potentiometer wires. See Method (i), Sec. 9-13.]

Precautions ; Same as 9 – 14.

Oral questions

1. What do you mean by the term e.m.f. of a cell ?

2. What is the difference between an e.m.f. and a potential difference ?

3 Instead of using a voltmeter, why do you use this method for determining the e.mf. of a cell ? Which of them is better and why ?

4. If instead of a milliammeter a standard cell is supplied to you, can you determine the e.m.f. of the unknown cell ? If so, how ?

5. What is the function of the resistance R' in series with the galvanometer ? Does the null point depend on its value ?

6. What is the fundamental condition for the success of your experiment ? When does the method fail ?

7. What happens if the negative terminal of E' be connected to the positive terminal of the potentiometer ?

Answers. 1. The e.m.f. of a cell is the potential difference between the terminals of the cell in open circuit. It is the work the cell does when unit charge (a coulomb) flows round the circuit.

2. An e.m.f. gives a charge a higher potential energy at the cost of some form of energy other than electrical. In a chemical cell, chemical energy is converted into the electrical energy of the charge. If, in some part of a circuit, some form of energy is converted into the electrical form, an e.m f. is said to exist there.

A potential difference is said to exist in a part of circuit in which electrical energy is converted into some other form of energy.

$$\text{Some form of energy} \underset{\text{p.d.}}{\overset{\text{e.m.f.}}{\rightleftharpoons}} \text{electrical form.}$$

3. It is an exercise in the use of a potentiometer. If it were merely a question of measuring a p.d. we could use a potentiometer.

The precision of the measurement depends on that of the ammeter or voltmeter used. If both could be read with the same precision, there is nothing to choose between the two.

4. Keeping other things unaltered, we replace the cell under investigation by the standard cell. The ratio of the two balancing lengths is also the ratio of the corresponding e.m.f.s.

5. R' protects the galvanometer from being ruined by a large current flowing through it. The position of the null point does not depend on the value of R'.

6. The fundamental condition to be satisfied for the success of the experiment is that *the e.m.f. E of the driver cell must be greater* than the e.m.f. E' to be measured. If $E' > E$, the method fails.

7. There will be no null point, as both cells will be driving current through the galvanometer in the same direction.

9·16. To measure a current with a potentiometer using known low resistance.

(a) When a voltmeter is given

Theory. When a current I flows through a resistance R, the potential difference between the terminals of the resistance is RI. This p.d. can be balanced on a potentiometer. If the length required for balance is l and e is the potential drop per centimetre of the potentiometer wire, then

$$RI = le \quad \text{or} \quad I = le/R. \quad \ldots \quad (9\text{·}16.1)$$

If e.m.f. of the driver cell is E, and R_p is the resistance of the potentiometer and R_b is the series resistance connected to it, then

$$e = \frac{E}{R_p + R_b} \cdot \frac{R_p}{1000} \quad \ldots \quad (9\text{·}16.2)$$

for a ten wire potentiometer, each wire one metre long.*

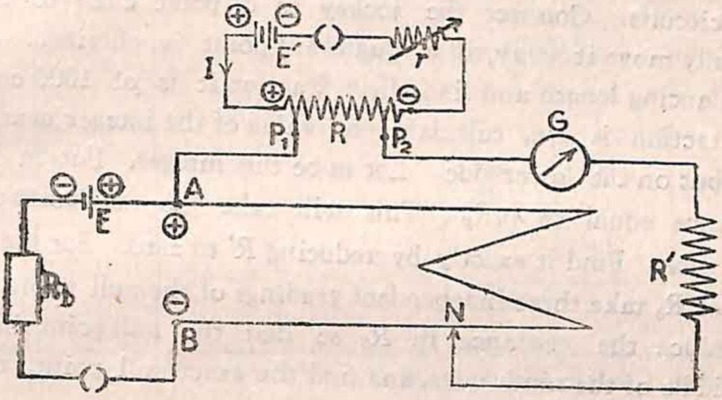
---

*This method of finding the potential drop per centimetre is preferred for the following reasons :

In ordinary circumstances a laboratory will not arrange for a current of over an ampere to be measured in this way ; the current is more likely to be lower, say 0·5 amp, to avoid running down of the storage cell used for providing this current. The standard low resistance is likely to be 0·1 ohm or less, preferably not higher, as it then rather ceases to be low. With 0·5 amp passing through 0·1 ohm, the voltage across the standard resistance is $0·5 \times 0·1 = 0·05$ volt. The driver cell (ordinary a lead storage cell) provides a p.d. of 2 volts across the potentiometer unless there is a series resistance. Thus the balancing length will be $0·05 \div (2 \div 1000) = 25$ cm or so. To take it on the tenth wire, the potentiometer current should be reduced to about one-fortieth its value. This means inclusion of series resistance of the order of forty times the potentiometer resistance. Since potentiometer resistances are around 20 ohms, a resistance box having 500 to 1000 ohms will be useful.

Combining 9·16.1 and 9·16.2 we can get I.

List of apparatus. (1) Potentiometer (AB; Fig 9.19); (2) driver cell E (a lead storage cell); (3) a resistance box to be used



Fig, 9.19

[AB = potentiometer ; E = driver cell : R_b = resistance box in series with potentiometer ; G = galvanometer , R′ = resistance for protecting galvanometer ; I = current to be measured ; R = standard resistance , P_1, P_2 = potential leads of standard resistance.]

in the potentiometer circuit (a box with about 1000 ohms preferred) ; (4) key (to be used in the potentiometer circuit) ; (5) galvanometer (G) ; (6) high resistance R' to be used in series with the galvanometer (value 5000 to 10,000 ohms) ; (7) a known low resistance (R) (one with potential leads preferred) ; (8) battery (E'), key, resistance (r) etc. for auxiliary circuit, the current I through which is to be measured.

[If the circuit in which the current is to be measured is not given, make up one with the following apparatus : (1) battery E' (two lead storage cells) ; (2) the standard resistance R (of value 0·1 ohm or so), (3) a rheostat or resistance box r (use a low value of resistance, say 20 ohms or less), and (4) plug key.]

Instructions. First find the resistance of the potentiometer with a P.O. box. Then connect as shown in Fig. 9.19. The positive potential lead P_1 of R must be directly connected to the positive terminal of the potentiometer.

Ascertain the values of the standard resistance, and of the e.m f. of the driver cell *in closed circuit.* Record them.

Put full value of resistance R' and zero value in R_b and close both circuits. Connect the jockey to a point close to A and gradually move it away till a rough null point is obtained. Note the balancing length and find what fraction it is of 1000 cm. If this fraction is $1/n$, calculate the value of the integer nearest to $n-1$, but on the lower side. Let m be this integer. Put in R_b a resistance equal to mR_p. This will take the null point to the tenth wire. Find it exactly by reducing R' to zero. For the same value of R_b take three independent readings of the null point.

Reduce the resistance in R_b so that the null point shifts to the middle of the ninth wire, and find the exact null point, taking three readings as before.

If time allows, get the null point on the eighth wire, and repeat.

Note the e.m.f. of the driver cell again in closed circuit.

Experimental results :

Resistance R_p of the potentiometer (using P O. box).

Ratio P : Q	Resistance R in rheostat arm	Direction of deflection	Inference
10 : 10	... ...	Right Left	R_p lies between ···and ···ohms
100 : 10			
1000 : 10			R =ohm

E.m.f of the driver cell (E) (to be read to two decimal places):

(*i*) Before experiment= ······

(*ii*) After experiment= ······

Mean= ······volts

Value of the given standard resistance $(R)=\cdots\cdots$ ohm.

Potentiometer resistance $(R_p)=\cdots\cdots$ohm (as determined with a P. O. box).

No. of obs.	R_b	R_p	$e=\frac{E}{R_b+R_p}\times R_p/1000$	Balancing length (l)		$I=\frac{le}{R}$
				l	mean l	
1.				(*i*) (*ii*) (*iii*)	...	...
2.					...	...
3.						...

$\therefore$ Mean value of $I=\cdots\cdots$amp.

[Note : Old storage cells often run down during work, particularly when a sizable current is drawn from them as in the auxiliary circuit. In such a case I will show a fall off with time.]

Method followed. (A brief statement)

1. The resistance of the potentiometer was determined with a P.O. box.

2. The potentiometer circuit for measuring current was set up as shown in the circuit diagram (Fig. 9.19). The e.m.f. of the driver cell and the value of the standard resistance were noted.

3. By trial, the null point was brought to the middle of the 10th wire. This required putting…ohms in R_b The null point was carefully determined.

4. By changing the resistance in R_b, the null point was shifted to the 9th and 8th wire, and the null points noted again.

5. From the data so secured the unknown value of the current was calculated.

(*b*) *When a milliammeter is given*

Theory. When a current I flows through a resistance R, the potential difference between the terminals of the resistance is RI. This p.d. can be balanced on a potentimeter. If the length required for balance is l and e is the potential drop per centimetre of the potentiometer wire then

$$RI = le \quad \text{or} \quad I = le/R \qquad \ldots \qquad (9\text{-}16.1)$$

If the current through the driver cell is i, and R_p is the resistance of the potentiometer, then

$$e = \frac{i}{1000} R_p \qquad \ldots \qquad (9\text{-}16.2)$$

for a ten wire potentiometer, each wire one metre long.

Combining 9-16.1 and 9-16.2 we get

$$I = \frac{iR_p l}{1000R} \qquad \ldots \qquad (9\text{-}16.3)$$

List of apparatus. Same as (*a*) except item (3). In item (3) you write, a milliammeter (0-200 *m*A range) and a rheostat.

Instructions. First find the resistance of the potentiometer with a P.O. box. Then connect as shown in Fig 9.20. The positive terminal lead P_1 of R must be directly connected to the positive terminal of the potentiometer. Ascertain the value of the standard resistance and record it.

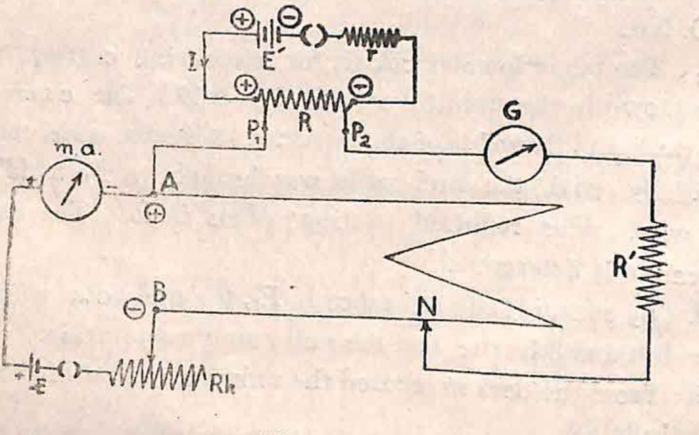


Fig. 9.20

AB = potentiometer ; E = driver cell ; Rh—rheostat in series with potentiometer ; m = milliamemter for measuring potentiometer current ; G = galvanometer ; R = resistance for protecting galvanometer ; E = current to be measured ; R = standard resistance ; P_1, P_2 = Potential leads of standard resistance.

Put full values of resistance R' and zero value in R_1 and close both circuit. Connect the jockey to a point close to A and gradually move it away till a rough null point is obtained. Gradually increase the resistance Rh untill you get the null point to the middle of the tenth wire. Find it exactly by reducing R' to zero. For the same value of Rh take three independent readings of the null point.

Reduce the resistance Rh so that the null point shifts to the middle of the ninth wire, and find the exact null point, taking three readings as before.

If time allows get the null point on the eighth wire, and repeat.

Experimental results.

Resistance R_p of potentiometer (using P.O. box).

Record as:in (*a*)

value of the given standard resistance $(R)=$ ···ohms.

No. of obs.	Current (i) in amp.	Null points			l in cm	$I=\frac{iR_p l}{1000R}$ in amp	Mean I in amp.
		On wire no.	Sc. reading in cm	Mean Sc. reading in cm			
1.	...	10th	... ...	...	...	...	
2.	...	9th	... ...	...	...	...	
3.	...	8th	... ...	...	...	...	

∴ Mean value of $I=$ ·· amp.

Method followed.

1. The resistance of the potentiometer was determined with a P.O. box and the value of the standard resistance was noted.

2. The circuit was constructed as shown in the circuit diagram.

3. By trial the null point was brought to the middle of the 10th wire. The milliammeter reading and the null point were carefully noted.

4. By changing the resistance is *Rh*, the null point was shifted to the 9th and 8th wire, and the null points noted again.

5. From the data so secured the unknown value of the current was caculated.

Precautions. Same as 9-14.

Oral questions

1. What is an electric current ?

2. What are the units in which it may be measured ? How are they related ?

3. Since a current may be measured by an ammeter, why do you follow this method of measurement ?

4. What is a potentiometer ? State briefly the principle of the potentiometer. In this experiment are you mearuring a current or a p. d. ?

5. Why are potential leads provided with a standard resistance ?

6. If the standard resistance were larger than what you are using, would R_b have to be increasd or diminished to get the null points at the same places ?

7. In what other ways can you find the drop of potential per centimetre of the potentiometer wires ? Would any of them be more accurate than this method ? Can you explain why you have chosen this method of measuring the drop ?

Answers. 1 An electric current in a wire is a one-way flow of the free electrons in it.

2. The SI unit is the *ampere*. There was an absolute elecromagnetic unit (e.m.u.) with no special name. Sometimes it was referred to as the abampere. 1 e.m.u. = 10 amperes.

3. This method can give a more precise value than an ammeter.

4. See Sec. 8-7. A potentiometer always measures a p. d. If this p.d. is an *Ir* drop, *I* can be found when *r* is known and vice versa.

5. The resistance between these two leads has the specified value.

6. In this *Ir* drop, if *r* increases the drop will also increase. So the potential drop per centimetre has to be increased to get the null points at the same places. This means that the current through the potentiometer should be increased. Hence the resistance in series with the potentiometer must be reduced.

7. See end of Sec. 8-7. Using a *standard cell* (of accurately known e.m.f. ; Method III of that section) is the most accurate.

The present method is more accurate than the one that uses an ammeter for measuring the p. d. per cm. but less accurate than the standard cell method. I should prefer a standard cell if I could get it.

9-17. To plot the e.m.f.—temperature curve for a thermocouple and hence to determine thermoelectric power

Theory. (i) **E.m.f.—temp. curve.** When one junction of a thermocouple is kept at a constant temperature t_1 and the other junction is heated to a higher temperature t_2, an e.m.f. acts round the circuit. The direction of the e.m.f. depends on the pair of metals used and the temperatures of the junctions.

The e.m.f. so developed may be measured by balancing it against a potential drop which can be calculated.

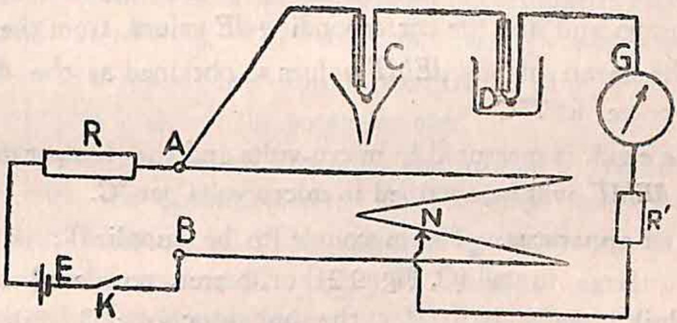


Fig. 9.21

In the arrangent as shown in Fig. 9.21, E is the e.m.f. in volts of the driver cell in the potentiometer circuit, R_b is the resistance in series with the potentiometer and R_p is the resistance of the potentiometer formed of a uniform wire of length L. The drop of potential e per unit length of the potentiometer is given by

$$e=\frac{E}{R_b+R_p}\cdot\frac{R_p}{L}. \qquad \ldots \qquad (9\text{-}17.1)$$

If l is the length of the potentiometer wire against which the thermo-e.m.f. E' is balanced, then

$$E'=le=\frac{E}{R_b+R_p}\cdot\frac{R_p}{L}.\,l \qquad (9\text{-}17.2)$$

By varying the temperature t_2 of the hot junction and measuring the corresponding e.m.f. a curve may be plotted with the temperature of the hot junction as abscissa and thermo-e.m.f. as ordinate.

(ii) **Thermoelectric power.** To determine the thermoelectric power dE/dT for the given pair of metals at a temperature $T°C$, draw a tangent to the curve at the point corresponding to the temperature $T°$C of the hot junction. Measure the ordinate and the intercept on the x-axis between the foot of the ordinate and the point at which the tangent intersects the temperature axis. The value of the ordinate divided by that of the intercept measures dE/dT at $T°C$.

Alternatively, measure a distance $dT = \pm 2°$ or $\pm 3°$ about $T°$ on the graph and find the corresponding dE values from the graph. Take the mean of the dE/dT values so obtained as the thermoelectric power at $T°$C.

If the e.m.f. is measured in micro-volts and the temperature in °C then dE/dT will be obtained in micro-volts per °C.

List of apparatus. Thermocouple (to be supplied) ; powdered ice in a large funnel (C, Fig. 9.21) or, better, powdered ice in a thermoflask ; water bath (for the hot junction ; D. Fig. 9.21) ; resistance boxes R and R′, both of high value ; a storage cell (E) ; key (K) ; volt-sensitive galvanometer (G) ; thermometer (preferably $\frac{1}{10}$ or $\frac{1}{5}$ degree).

Instructions. Prepare the thermo-couple*. Determine the resistance R_p of the potentiometer by means of a P.O. box.

Arrange your apparatus as shown in Fig. 9.21. The junction C is placed in a bath of melting ice. The other junction D is placed in a fairly large beaker containing water. A sensitive thermometer (preferably reading to 1/10th of a degree) is placed in the water bath with its bulb very close to the junction. The junctions should be kept fixed in the baths by means of separate clamps and be so placed as to give them *equal cover of the bath material on all sides.*

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*Ordinarily a copper-constantan or a copper-iron thermocouple is used for the experiment. To prepare a thermocouple, take three pieces of wire, one of constantan or iron and the other two of copper, each about one metre long. Clean the ends and join one end of each of the copper wires to the ends of the constantan wire by twisting and then soldering the junctions with the minimum amount of solder. The junctions should be small, preferably not more than 2 or 3 mm in length. Introduce the copper wires through two thin glass tubes, each about 10 inches long, and allow them to rest near the junctions. This ensures that the metals forming the couple will not touch each other at any point other than the junctions.

Measure the e.m.f. E of the driver cell by means of an accurate voltmeter correct to 2 decimal places. Ascertain whether there is any zero error of the voltmeter.

The drop of potential to be measured does not ordinarily exceed a few thousand micro-volts. To avoid unnecessary calculations, it is convenient to arrange for a drop of potential of 10 or 5 micro-volts per centimetre length of the potentiometer.

This may be easily done by introducing the necessary resistance R_b in series with the potentiometer. The required value of R_b may be calculated from Eq. 9-17.1 by substituting the values of E and R_b and putting e equal to 10^{-5} or 5×10^{-6} volt.

To check whether similar poles of the driver cell and the thermocouple have been connected together, make a momentary contact of the jockey first at one end of the potentiometer wire and then at the other end. If the deflection of the galvanometer on both occasions is in the same direction reverse the polarity of the driver cell. For a copper-constantan couple, copper is positive at the hot junction. For a copper-iron couple, iron is positive at the hot junction.

Note the null point when the hot junction is in the water bath at the room-temperature. Raise the temperature of the bath by steps of 8 to 10°C, hold it constant for at least two minutes and note the corresponding null point. In this manner proceed as far as you can, but don't have the juuction in boiling water. Use a hypsometer instead.

Make sure that the cold junction remains at the temperature of melting ice throughout the experiment. Heat carried by the conducting wires melts the ice round the cold junction, forming an air pocket round it. The temperature of the cold junction therefore increases. To prevent it pierce the ice bath from time to time with a glass rod and press the powdered ice. As ice melts, put more powdered ice on the top.

Draw a graph with temperature of the hot junction as abscissa and the corresponding e. m. f. as ordinate. Mention the temperature of the cold junction on the graph. The curve will pass through a point on the x-axis coresponding to the temperature of the cold junction.

Thermoelectric power. If time permits take four or five readings at intervals of 2° or 3°C near about the temperature of the hot junction at which the thermo-electric power is to be determined. Take care to keep the water bath constantly stirred when observing the null points.

Draw a tangent to the curve at the point corresponding to the temp. $T°C$ at which $\frac{dE}{dT}$ is to be determined. Find $\frac{dE}{dT}$ at T°C from the graph.

Experimental results :

Resistance R_p of the potentiometer = ···ohms

(The value may be supplied by the laboratory. If not, determine it with a P.O. box, recording the observation briefly.)

Zero error of voltmeter = nil (or ···V to be added / subtracted)

E.m.f. of the driver cell = ···volts (to 3 significant digits)

(corrected value if there is zero error)

Box resistance R_b to get a drop of 10^{μ}A/cm of bridge wire

= ···ohms.

(Find this value by calculation. Show the calculation on the left page.)

Temperature of cold junction = ··· °C.

(If it is room temperature, check it every 10 minutes and record.)

E.m.f.-temperature record :

Temp.							
Null pt.							
E. m. f (in μV)							

Graph : A graph was drawn with temp. along the x-axis and e.m.f. (in μV) along the y-axis. The origin represents the temp. of the cold junction.

Thermo-electric power. (Draw the tangent to the curve at the temperature at which the thermo-electric power is to be determined. Find the slope of the tangent line. This slope is the value of the thermoelectric power at the temp. at which the tangent was drawn.)

From the tangent to curve at···°C, the thermoelectric power at that temp.$=\cdots\mu$V/···°C.

Method followed : (A brief statement)

1. The circuit was constructed as shown in the circuit diagram.

2. The resistance of the potentiometer was determined with a P.O. box.

3. The e.m.f. of the driver cell was noted. A resistance of ···ohms was put in series with the potentiometer to give a potential drop of 10 μV/cm along the potentiometer wires.

4. The cold junction was placed in melting ice bath/at room temperature.

5. The polarity of the thermojunction was tested and the right connections made.

6. The temp. of the hot bath was increased by steps of about 8°C. At each value the temp. was held constant for about 2 minutes and the balance point obtained. The balancing lengths were converted into μV.

7. The e.m.f-temp. curve was drawn from the data obtained.

Precautions. 1. The circuit must be protected against heat from the burner. However well-shielded the burner may be, there is a great risk of undesired thermo-e.m.f. appearing in the circuit. To eliminate the effect follow the instruction given in Sec. 9-1(9).

2. If the cold junction is to be kept at the room temperature, place it in a large beaker of water. Test the temperature of the water periodically. If it changes, complications will arise in your work. In such a case, draw the curve of e.m.f. against *difference* of temp. of the two junctions. (But this is not proper. Try to keep the cold junction at a constant temperature. If need be, mix a little cold water in case the temperature rises)

Oral questions

1. What is the p.d. per mm of the potentiometer wire ? Why have you preferred this value ?

2. What is the order of magnitude of the e.m.f. you are measuring ? Can a voltmeter be used ?

3. Should all the wires of the potentiometer be the same material and diameter ?

4. What kind of galvanometer would you prefer for this work and why ?

5. What kind of thermocouple would you prefer for this work ? Why ?

Answers.

1. I have arranged for a drop of 1μ V/mm along the wires. This is a convenient value, both for practical purpose of calculation.

2. The maximum e.m.f. to be measured is of the order of 2-3 thousand microvolts at the most. It depends on the metals of the couple.

A Voltmeter is not suitable. (A microvoltmeter has to be an electrostatic one.)

3. Yes, we want a uniform drop of potential along the wires. So the resistance per cm must be the same throught.

4. A volt-sensitive galvanometer, that is, one with an appreciable deflection when a small p.d. is applied to its terminals. (See Sec. 8-2. 6.)

5. A copper-iron or a copper-constantan thermocouple. The former has a thermoelectric power of about 54 μV/°C between 0° and 100°C. The value for the latter is about 40μV/°C in the same range.

CHAPTER 10

ELECTRONICS

10-1. Thermionic emission : Diodes and Triodes.

Electron emission from a heated metal surface is very similar to the evaporation of a liquid from its surface. When a liquid is heated, an increasing number of molecules acquire sufficient energy to overcome the attractive force of the liquid surface and are evaporated. The number of evaporating molecules increases rapidly with rising temperature. Similaly, when a metallic body is heated, an increasingly larger number of electrons overcome the retaining forces at the metal surface and are "boiled off" from the metal.

The number of electrons evaporated per unit area per second from a metal surface depends on the nature of the surface and its temperature. The relation between the emission current I per unit area and the absolute temperature T (kelvin) is given by Richardson's equation, namely,

$$I=AT^2 \exp(-b/T)$$

where A is a constant for the emitting surface, different for different emitters. b is a sort of a measure of the work an electron must do in escaping from the emitter surface. For oxide coated emitters, A is of the order of 0·01 (amp. per cm^2 per deg.^2) and b is about 12,000 K (kelvin). Oxide coated cathodes (barium-strontium oxide) are operated at about 1000 to 1150 K.

Methods of heating.

Electron emitters are heated elctrically either *direcly* or *indirectly*. In the direct method, electric current is applied to a *filament* wire which serves as emitter. In indirect heating, electric current is applied to a separate heater element, placed inside a

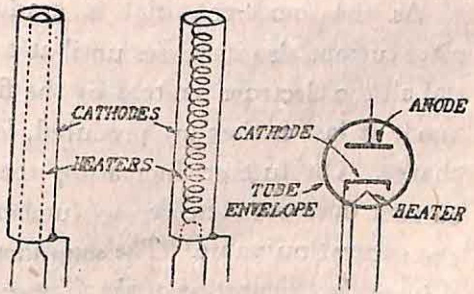


Fig. 10.1

cylindrical cathode that serves as emitter (Fig. 10.1). Indirectly heated cathodes use oxide-coated emitters.

10·2. Diode. A diode consists of a cathode, which serves as an emitter of electrons, and a plate or anode surrounding the cathode. It acts as collector of electrons. Both electrodes are placed in a higly evacuated envelope of glass (or metal). The plate is generally a hollow metallic cylinder made of nickel, iron, molybdenum, etc.

Action. When the filament of a valve is heated it emits electrons, which gather around it. This atmosphere of electrons gathered around the filament is called the **space charge.** The density of electrons forming the space charge goes on increasing gradually. But due to repulsion between like charges, some of the electrons are sent back into the filament. As the space charge increases, the number of electrons sent back into the filament also increases, until a dynamical equilibrium is finally established when the number of electrons emitted equals the number returned.

Now, imagine a small positive potential to be applied to the plate. In this condition an electron current flows from the cathode to the plate (*i.e.*, the conventional current flows from the plate to the cathode). The value of the current is determined by the anode-potential as well as the space charge.

As the anode-potential is gradually increased, the anode or plate-current also increases until at a particular high anode potential all the electrons emitted by the filament are collected by the anode as fast as they are produced, leaving none to form the space charge. On further increasing the anode-potential the anode current does not increase any further, and is said to have reached the saturation value. *The saturation value of the current depends only on the temperature of the filament and not on the anode potential.* An increase of temperature (*i.e.*. of the current which heats the filament) increases the saturation current.

In oxide-coated cathodes we do not seek to get the saturation current. This current is so large that in trying to draw it, the oxide-coat will be damaged.

10-2.1. Diode characteristics. The relation between the plate-current in a diode and the plate-to-cathode voltage can be represented by a **characteristic curve,** obtained by plotting the plate-current (I_a) values for different values of the applied voltage (V_a). The **diode characteristics** for a typical diode tube and various cathode operating temperatures (which are controlled by the filament heating currents) are shown in Fig. 10.2.

Note that all the curves are the same at low plate-voltages. Here the negative space charge is most effective in limiting the flow of electrons. The plate-current at this stage is completely controlled by the plate-voltage, and is *independent of the emitter (cathode) temperature.* Here the plate-current is said to be **space-charge limited.**

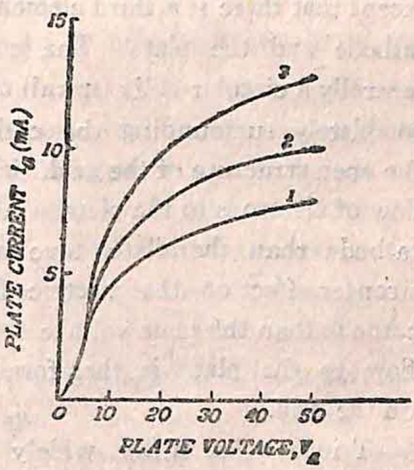


Fig. 10.2

[Diode characteristic I_a-V_a curves. Curve 1 is at some low operating temperature, curve 2 at medium and curve 3 at high operating temperatures. The curves are for an oxide-coated cathode.]

As the plate-voltage is increased, more electons are drawn to the plate and the plate-current increases. The characteristic curve is gradually flattened with increase in plate-voltage. When the rate of emission of electrons becomes equal to the rate of collection by the plate, the plate-current becomes independent of the plate-voltage. This current is called the **saturation current.** It is *emission-limited* and exists only in the high plate-voltage region. For tungsten and thoriated tungsten emitters, saturation takes place at relatively low plate-voltages as their emission, controlled by Richardson's equation, is rather low. Oxide coated emitters do not have such a specific emission saturation value. The plate-current, though tapering off at high plate-voltages (Fig. 10.2.), never becomes completely independent of the plate-voltage. At very high plate-voltages oxide-coated cathodes may become damaged because of the abnormally large emission. In general, **electron tubes are operated in the space-charge limited (low voltage) region.**

10-3. Triode. The triode is similar in structure to the diode except that there is a third element, the **control grid**; between the cathode and the plate. The control grid, or simply the grid, is generally a circular helix (spiral) of a number of turns of fine wire completely surrounding the cathode and close to it. Because of the open structure of the grid, it does not directly obstruct the flow of electrons to the plate. As the grid is much closer to the cathode than the plate, a voltage applied to the grid has a much stronger effect on the electric field between the plate and the cathode than the same voltage applied to the plate. The electron flow to the plate is therefore strongly affected by the voltage on the grid.

Triode tubes differ widely in size and electrode spacing, depending on its power rating and desired function.

A triode requires *three* operating voltages, one on each electrode, to operate correctly. The plate (or anode) of the tube is normally connected to a high positive voltage V_a with respect to the cathode to attract the stream of electrons. A relatively low voltage V_f (a.c. or d.c.) is connected to the filament or heater to bring the cathode to its proper emitting temperature and thus make available a supply of electrons. Finally, a voltage V_g is placed on the control grid to control the flow of plate-current. In the static condition of the tube, it is a fixed d. c. voltage called the bias, which is normally a few volts *negative* with respect to the cathode. Its purpose is to operate (or "bias") the tube on a definite point on its characteristic curve (similar to a diode characteristic), so that a certain amount of plate-current I_a is always flowing.

(Superimposed on this bias voltage is a varying or alternating voltage, usually called the **signal voltage.** The purpose of this voltage is to vary the flow of plate-current through the tube in strict accordance with the signal variations, so as to make the plate-current an **amplified** copy of the signal voltage. Amplification takes place, since a small variation in the signal voltage on the grid results in a large variation of the plate-current through the tube.

When there is no signal, the valve is operating in the **static condition.**)

The smallest negative voltage between grid and cathode that is just capable of cutting off the plate-current is called the **cut-off bias.** Bias voltages more negative than this cut-off value have no effect on the action of the tube. At cut-off bias the electrostatic field between the cathode and grid neutralizes that between plate and cathode.

Zero grid bias. When the grid voltage is zero, a plate-current flows due to the positive plate-voltage. The action is similar to that of a diode, except that the grid still has some retarding effect on the electrons because of its screening action. Electrons are not attracted to the grid itself, since it is at zero potential with respect to the cathode.

Positive grid bias. A positive potential on the grid produces a strong electric field helping the field due to the voltage on the plate. The plate-current therefore increases strongly and may soon reach saturation with increasing positive bias on the grid. Further increase will have no effect on the current. A positive voltage on the grid draws a **grid current,** electrons flowing from the cathode to the grid.

Electron tubes are generally operated at negative grid potentials with respect to the cathode.

10·3.1. Triode characteristic curves. The relationships between the plate-voltage, grid-voltage and plate-current in a triode can be conveniently summarized in the triode's characteristic performance curves. These characteristic curves are represented as relations between two quantities, while the third is held constant. Thus we can have

(i) The anode or plate-current (I_a) plotted as a function of varying plate-voltages (V_a), when the grid-voltage (V_g) is held at some fixed value. This is known as the plate-current-plate-voltage (I_a-V_a) characteristic (Fig. 10.3*a*).

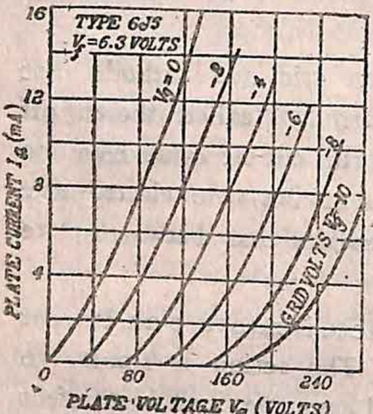


Fig. 10.3(a)

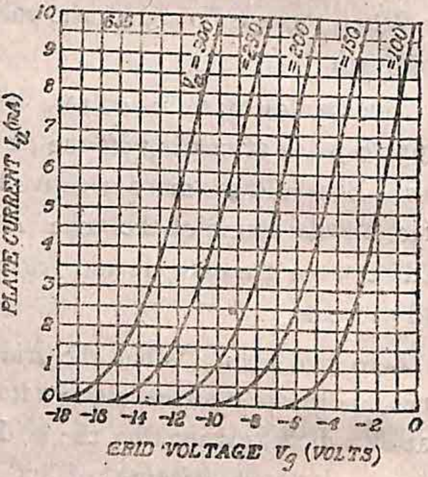


Fig. 10.3(b)

(ii) The plate-current (I_a) caused by varying the gird-voltage (V_g), holding the plate-voltage (V_a) at a constant value. This is called the plate-current grid-voltage (I_a-V_g) characteristic of the triode (Fig. 10.3*b*).

A whole set of curves of one kind, (I_a-V_a) or (I_a-V_g), can be drawn by giving the other quantity (V_g in the first case and V_a in the second case) different values. Such a set of characteristic curves is known as a **family of static triode characteristics.** The term *static* denotes that the characteristics are obtained when vorious *steady* voltages are applied to the tube's electrodes.

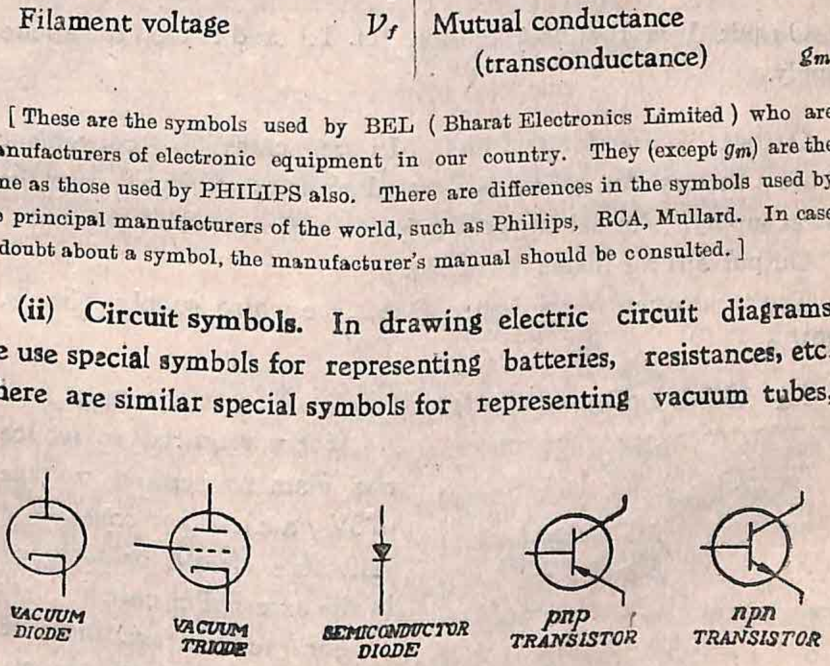
(*Dynamic characteristics* are obtained under actual operating conditions, with a signal voltage applied and a load resistance inserted into the plate circuit to extract power from the tube.)

10·4. Some conventional symbols. (i) Parameter symbols. Though there is no uniformity regarding symbols used in connection with tube parameters and transistor parameters, the symbols are rather few. We shall use the following symbols.

Parameter		*Parameter*	*Symbol*
Anode (plate) voltage	V_a	Filament current	I_f
Anode current	I_a	Amplification factor	μ
Grid voltage	V_g	Anode (plate) resistance (internal)	R_i
Grid current	I_g		
Filament voltage	V_f	Mutual conductance (transconductance)	g_m

[These are the symbols used by BEL (Bharat Electronics Limited) who are manufacturers of electronic equipment in our country. They (except g_m) are the same as those used by PHILIPS also. There are differences in the symbols used by the principal manufacturers of the world, such as Phillips, RCA, Mullard. In case of doubt about a symbol, the manufacturer's manual should be consulted.]

(ii) Circuit symbols. In drawing electric circuit diagrams we use special symbols for representing batteries, resistances, etc. There are similar special symbols for representing vacuum tubes, junction diodes and transistors. The few of them which we shall require are shown below.



Fig, 10.4

10·5. Some accessories for electronic experiments.

(i) **Power supply.** It is an instrument for supplying *regulated* d. c. for experiments. By 'regulated' we mean that the voltage it supplies is independent of the load and line voltage variation.

The commercial instruments for valve experiments in general have three outputs, namely.

1. 0 – 300 volt (d. c.) ; regulated and continuously variable, capable of supplying a maximum current (30 mA is a typical value).
2. 0 – 30V or 0 – 100 V (d. c.) ; continuously variable but capable of supplying very small current.
3. 6·3V (a. c.) ; capable of supplying 3 to 5A current.

Output 1 is the high tension (H. T.) and is used for anode supply.

Output 2 is used for grid bisa. (In some cases it is convenient to use a battery for grid bias instead of using output 2 from the power supply. An old power supply often gives trouble.)

Output 3 is for filament heating.

The *input power* to the instrument is the mains supply, that is, 220V a. c.

Fig. 10.5 is a diagram of a typical panel of a power supply.

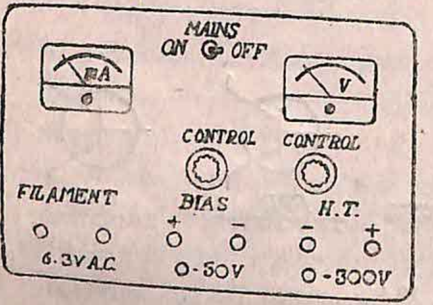


Fig. 10.5

If it is required to reduce the filament heating voltage (6·3V a.c.), a controlling resistance should be included in the external circuit.

For taking readings of currents and voltages in an experiment, we do not use the milliammeter and voltmeter on the panel as they are not accurate enough for the purpose. For taking readings, separate meters are included in the circuit.

(ii) Chassis arrangement of valve experiments. Chassis (pronoudced 'shas-i') means the framework to which the parts of a receiver, amplifier, etc. are attached, together with the assembled parts. Makers of laboratory instruments may be asked to prepare the necessary chassis.

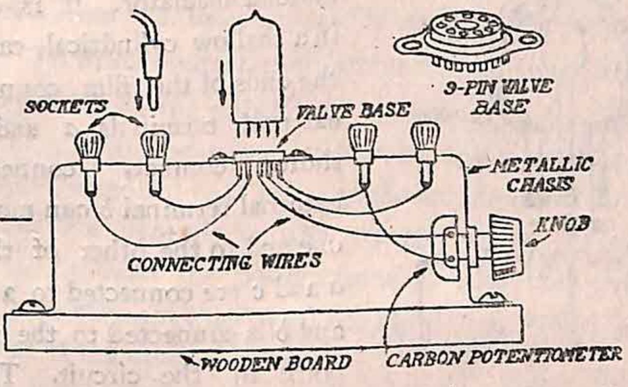


Fig. 10.6 (a)

[Internal arrangement in a chassis for a valve experiment]

Fig. 10.6 (a) represents the internal chassis arrangement for a valve experiment. Fig. 10.6(b) is the external appearance.

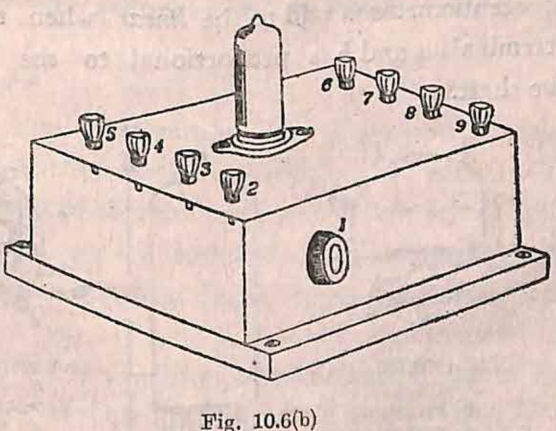


Fig. 10.6(b)

[External appearance of the chassis. 1 = knob for adjusting carbon potentiometer ; 2, 3, 4 = three terminals of carbon potentiometer ; 5 = grid terminal ; 6 = anode terminal ; 7 = cathode terminal ; 8, 9 = filament heating. These indicated connections are symbolic. In an actual case, the connections are indicated on a card attached to the chassis.]

(iii) **Carbon potentiometer.** A carbon potentiometer (Fig. 10.7) consists of a thin film of hard carbon deposited on an open, annular insulator. It is enclosed in a shallow cylindrical case with the ends of the film connected to external terminals *a* and *c*. A sliding contact, connected to external terminal *b* can move from one end to the other of the film. *a* and *c* are connected to a battery, and *b* is connected to the required point in the circuit. The p.d. applied between one end of the battery and this point can be varied by rotating the shaft which causes the sliding contact to move.

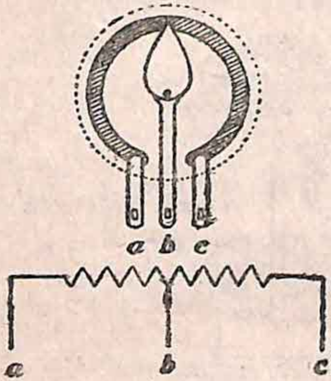


Fig. 10.7
[Carbon potentiometer]

The resistance of the film is high. (We shall use a value of 1 megohm.) The high resistance causes only a minute current to flow through the film or the circuit.

A carbon potentiometer is said to be *linear* when the voltage between the terminals *a* and *b* is proportional to the amount of rotation of the shaft.

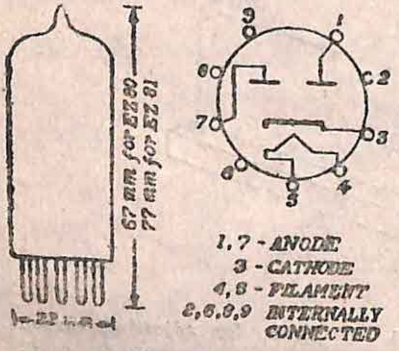


Fig. 10.8(a)

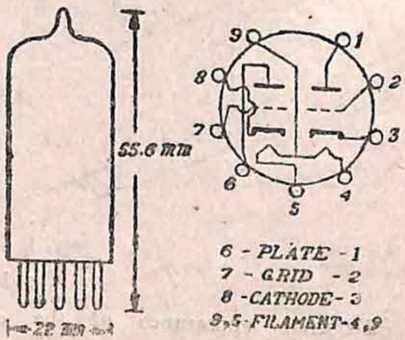


Fig. 10.8(b)

(iv) **9-pin valve base.** Valves are mounted on standard bases. Pin connections inside the valves for the double diode and twin triode we have advocated, are shown in Fig.s 10·8 (a) and 10.8(b) together with the dimensions of the valves. Wires soldered to the leads from the bases connect them to sockets of the chassis.

10-6. To draw characteristic curve of a vacuum diode.

Theory. When the cathode of a vacuum diode is emitting electrons at constant temperature (that is, with a constant filament heating voltage applied to it) the anode-or plate-current flowing through the tube depends on the voltage applied to the plate. The relation between the plate-current I_a and the plate-voltage V_a for a fixed filament (heating) voltage (V_f) is called a *characteristic curve* of the diode.

Diodes are generally meant for operating at a fixed filament voltage. The characteristic curve corresponding to this voltage is the most important. Other curves may be drawn for different values of V_f.

List of apparatus. Diode under test [No. EZ 80 and EZ 81 (BEL) recommended* for the use] mounted properly on a chassis ; standard variable power supply ; voltmeter (30V full-scale, D.C.) ; Ammeter (100 mA full-scale, D.C.) ; Resistance box (about 1000Ω max.)

[*Alternative to power supply.* For diode experiments, the plate-voltage required is within 20V. To avoid a power supply, one can use a battery stack of 14 cells (1·5V each). The anode-voltage can then be changed in steps of 1·5 volts. The filament heating voltage can be supplied from a simple transformer of output voltage 6·3V, the input being the mains supply at 320V A.C.]

Instructions (if working with power supply). 1. Connect the components as shown in the circuit diagram (Fig. 10.9a). Check the connections carefully.

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*Both these are *double diodes.* There are two separate plates or anodes inside, but only one cathode which is common to both. Either of the plates can be used for experiment.

2. Keep the H T. control knob of the power supply in its minimum position and switch on the supply. Introduce a resistance of 200Ω in the resistance box R. After a few minutes (2 or 3) the cathode will reach a steady temperature and H. T. (high tension) will be available from the supply.

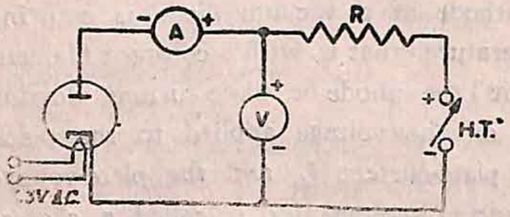


Fig. 16.9(a)

3. Rotate the H.T. controlling knob slowly in the clockwise direction to apply a desired voltage across the cathode and the plate.

4. Read and record the plate voltage and plate current from the voltmeter and ammeter respectively. Do so for each one-volt increase of plate-voltage.

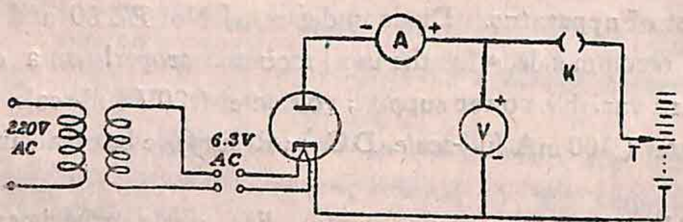


Fig. 10.9 (b)

5. Do not increase the plate-voltage any further when the plate-current reaches a value of about 50 mA. (This may damage the diode, which is of the oxide-coated type.)

6. Before switching the power supply off, rotate the H.T. controlling knod to the minimum value.

7. If it is required to draw characteristics at lower temperatures put a variable resistance (say 5Ω—3A) in series with the filament, and an A.C. voltmeter (0-20V range) across the filament. Use voltages 6·3V, 5·9V, and 5·3V. These would give I^2 values roughly as 40, 35, 30.

Instructions (if working with battery stack). 1. (As for the 'Power supply' method, but use Fig. 10. 9b.)

2. Switch on the filament supply, keeping the key K open.

3. Connect the moving terminal (Wandering plug) T to the 1.5V point of the battery stack.

4. After 2-3 minutes of switching the filament on, close the key K. Read the plate-voltage. V_a and plate-current I_a from the voltmeter and ammeter respectively.

5. Shift the terminal T to the next higher voltage point (that is, increase the voltage by 1·5V), and record the V_a and I_a values. Go on doing so for each increase of 1·5V until I_a is about 50 m*A*. Do not go beyond this value.

6. Open the key K and switch off the filament supply.

7. (As in item 7 above.)

Experimental results :

Valve no……

I. Filament voltage=…*V*		*II.* Filament voltage=…*V*		*III.* Filament voltage=…*V*	
V_a(in volts)	I_a(in mA)	V_a(in volts)	I_a(in mA)	V_a(in volts)	I_a(in mA)

The graphs are drawn of I_a against V_a on the same sheet, marking v_f on each curve.

Method followed :

[Write it brifly on the model of other experiments. telling about the actual method you have follwed (Power supplp method or Battery stack method).]

Precautions :

1. The prescribed limits of voltage and current appropriate to to the valve must not be exceeded.

2. For indirectly heated cathods, a heating up time of 2-3 minutes must be allowed before applying the anode voltage.

3. Before switching off the filament supply, the H.T. should be removed.

Oral questions

1. On what factors does the plate-to-cathode current in a diode depend? State briefly the nature of dependence on each.

2. What is the direction of the conventional electric current within the valve?

3. What is saturation current? On what does it depend? Will you get this value here? Why? What is the difference in external appearance between a directly heated and an indirectly heated cathode? In symbols?

4. What is a *double diode*? What is its advantage? Are you using one such? Why?

5. What is the order of magnitude of the vacuum inside the diode? Why do we want a vacuum of this order?

6. What is the difference between half-wave and full-wave rectification? What does your diode do?

7. A diode is said to work as a rectifier and as a detector. What is the difference between the two?

8. What is a space charge?

Answers.

1. It depends both on the temperature of the cathode and on the plate-voltage relative to the cathode. As filament temperature increases, the current increases according to Richardson's equation. As voltage increases, the current increases as shown in Fig. 10.2.

2. Inside the valve, the *electrron curent* flows from the cathode to plate. Outside the electron current flows from plate to the cathode. The *coventional electric current* is the direction of flow of a *positive* charge. This is opposite to that of the electron current.

3. When all the electrons emitted by the cathode are drawn to the plate, none being left to form a space charge, the current is said to be a saturation current. Its value depends only on the temperature of the filament.

In an oxide-coated valve, we do not try to reach the saturation current, as this is likely to damage the oxide coating. The valve here is oxide-coated and indirectly heated. Valves which are indirectly heated have, besides the filament, an extra electrode each, which is the cathode.

4. A double diode has two separate (and independent) plates, but a common cathode, within the same envelope. It is more economic to use a double diode in a full-wave rectificaton circuit than two single diodes.

Single diodes are commonly not much used. Hence their manufacture is uneconomic. Double diodes are more easily available than single diodes.

5. The degree of vacuum is 10^{-3} mm Hg or better. If there is an appreciable number of gas molecules in the value, many electrons will be lost in ionizing them. The positive ions will crash on the cathode and cause complications.

6. In half wave rectification, one half of an alternate cycle is suppressed. So only half the energy is transmitted. In full-wave rectification all the half-cycles are made to flow in the same direction. So the full energy of the supply is received. In this case, there is no question of rectification. A double diode is used for full-wave rectification.

7. When the a.c. to be rectified carries very small power, as in radio receiving sets, we call it *detection*. When the power is appreciable or large, the operation is called *rectification*.

8. Space charge is the cloud of electrons that gathers round the cathode in a valve when all the emitted electrons are not being drawn to the plate.

10·7. To draw the static characteristics of a triode and hence to determine its amplification factor.

Theory. The graphical relation between the plate-voltage and the plate-current when the grid-voltage is held constant, or between the grid-voltage and plate-current when the plate-voltage is held constant, is called a **static characteristic** of a triode. From a family of characteristics of any one of these two kinds, the amplification factor of the triode can be determined. (Potentials are measured with reference to the negative end of the cathode.)

The **amplification factor** μ of a valve is defined as the ratio of the change in plate-voltage (δV_a) required to produce a small change in the plate-current to the change in the grid-voltage (δV_g) required to produce the *same change* in the plate-current (that is, $\mu = (\delta V_a / \delta V_g)$ with I_a constant). The amplification factor of a triode is a measure of the relative effectiveness of the control grid in overcoming the electrostatic field produced by the plate.

[**Note.** From the characteristic curves in the figure below (Fig. 10.10), it is clear that an increase in anode current BA may be produced either by changing the

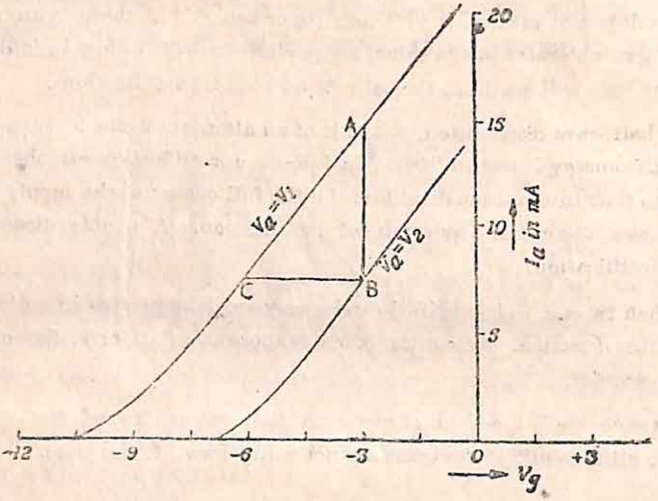


Fig. 10.10

anode potential from V_2 to V_1 (at constant grid potential) or by keeping the anode potential V_1 constant and changing the grid potential from C to B. Thus the amplification factor μ is given by

$$\mu=\frac{V_1-V_2}{BC}$$

Knowing V_1, V_2 and measuring BC, μ may be determined.

The value of μ is constant only for the straight portions of the characteristic curves. A, B and C should be taken on the straight portions of the curves.]

List of apparatus. Triode for experiment [Valve no. ECC 83* (BEL) mounted on a suitable chassis is recommended]; Power supply (0-300 D.C.; maximum current of 15 mA will be enough); Ammeter (10 mA full-scale, D.C.); Two voltmeters (one of 300V full-scale, D.C., and another of 10V full-scale, D. C.); Battery (2×1·5V) and carbon potentiometer (1MΩ, linear) for grid bias supply.

(I_a-V_a curves at given V_g values)

Instructions. 1. Connect the components as shown in the circuit diagram (Fig. 10.11). Check the connections carefully.

---

*This is a twin triode. Single section may be used for the experiment.

2. Keep the H. T. control knob at the position of lowest voltage and switch on the power supply. Note the filament voltage.

3. Adjust the potentiometer R to apply zero grid voltage.

4. After 2 to 3 minutes, rotate the H. T. control slowly to apply 25V across the cathode and plate. Read the plate-current and plate-voltage from the ammeter and voltmeter. Note down the readings for each 25V increase in plate-voltage. (For ECC 83 the maximum current should not exceed 5 mA.)

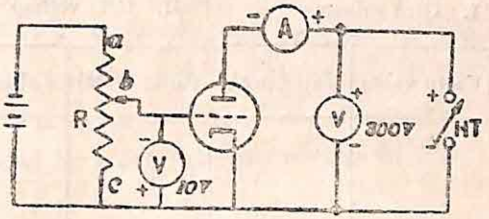


Fig. 10.11

5. Bring down the applied plate-voltage to the lowest values. Change the grid-voltage to $-0{\cdot}4$V. Apply the plate-voltage and take readings as in 4 above.

6. Take readings as in 5 with other negative grid-voltages (say, $-0{\cdot}8$, $-1{\cdot}2$, $-1{\cdot}6$, etc.). Unless otherwise directed, take three different V_g values.

7. Draw I_a-V_a curves for different V_g values on the same graph paper.

8. Find μ from the straight portions of the graph for some chosen I_a. (Or, follow the method indicated in Fig. 10. 10)

Note. If an ECC 83 valve is used, δV_a should be confined to about 0·4V if the straight portions of the characteristic curves are to be utilized for determining μ.

The voltages for which the straight portions of the characteristic curves are obtainable, depend on the make of the valve. The student should ascertain from the teacher the V_a, V_g and I_a values with which he should confine himself, and which should not be exceeded.

Experimental results :

Valve No······

Filament heating voltage=···V

I. Gird voltage=···V		II. Grid voltage=···V		III. Grid voltage=···V	
V_a(in volts)	I_a(in mA)	V_a(in volts)	I_a(in mA)	V_a(in volts)	I_a(in mA)

Graphs I, II, III are drawn for the three grid-voltages, plotting V along the x-axis and I along the y-axis.

Amplification factor. From the graphs, it is found that I_a has the same value (···mA) when (i) either $V_a=$···V with $V_g=$···V, or (ii) $V_a=$···V with $V_g=$···V.

∴ At constant current, a change δV_g in grid-voltage=···volt produces the same effect as a change (δV_a) in plate-voltage=··· volt.

Hence, by definition, the

amplification factor $\mu=\delta V_a/\delta V_g=$···V/···V=···.

Instructions (I_a-V_g curves at given V_a values)

1, 2 and 3. As before.

4. Ask the teacher at what constant plate-voltages you are required to draw the characteristics and the limiting value of the plate-current which should not be exceeded. [These depend on the make of the valve. For ECC 83, these voltages may be 230V, 250V and 270V (or thereabouts and the current, 5 mA]

5. After 2-3 minutes, rotate the H.T. control gradually till the lowest of these plate-voltages is applied. Read I (plate-current) and V_g (grid-voltage) from the ammeter and the voltmeter connected between the cathode and the grid. *Reduce* the grid bias by steps of say, 0·5 V and take the I_a-V_g readings until the plate current falls to too small a value.

6. Take similar readings for the two other plate-voltages.

7. Draw the three characteristic curves on the same graph paper, marking V_a on the corresponding curve.

8. Draw through some I_a value a straight line parallel to the V_g axis which cuts the curves on their straight portions. Find the amplification factor from the V_a, V_g values of these intersection points (as has been recommended for static characteristics at fixed V_g values).

Experimental results :

Valve No···

Voltage applied across the filament=···volts

I Plate-voltage=···volts.		II Plate-voltage=···volts.		III Plate-voltage=···volts	
Grid-potential (in volts)	Plate-current (in milli-amp.)	Grid-potential (in volts)	Plate-current- (in milli-amp.)	Grid-potential (in volts)	Plate-current (in milli-amp.)

Plot points on a graph paper representing grid voltages along the x axis and anode currents along the y-axis. Draw the three characteristic curves. On the curves mark the respective plate potentials.

Calculation for μ. Choose a point B on curve II (drawn with the higher plate-potential) and note the corresponding I_a value. Draw ABC parallel to the x-axis to intersect curve I at A and curve III at C. Take care that the points A, B and C are on the straight portions of the characteristic curves.

From curves I and II

I_a has the same value when (i) $V_g = \cdots$V and $V_a = \cdots$V(curve I) or (ii) $V_g = \cdots$V and $V_a = \cdots$V (curve II). Therefore, $\delta V_g = \cdots$ (difference of the two V_g values) produces the same effect on I_a as $\delta V_a = \cdots$(difference of the two V_a values).

Hence $\mu = \delta V_a / \delta V_g = \cdots \mathrm{V} / \cdots \mathrm{V} = \cdots$.

Similarly determine μ from I and III as also from II and III.

Result. ∴ Mean $\mu = \cdots\cdots$.

Method followed. 1. The circuit was arranged as shown in Fig. 10.11.

2. The filament heating current was adjusted to the prescribed value.

3. The plate-voltage was given a value of···, and the grid-voltage, a value of zero.

4. The grid-voltage was reduced by equal steps and the corresponding plate-current noted, the plate-voltage remaining the same. This was continued until about zero plate-current was reached.

5. Observations 3 and 4 were repeated for two other plate-voltages.

6. The graphs were drawn and calculation made as shown.

Note. 1. A set of characteristic curves drawn for different grid-potentials supplies the same information regarding the valve as the set of characteristic curves discussed first. Both sets are obtainable from the same arrangement of apparatus.

2. For triodes of low amplification factor, the saturation value of the current (for normal filament-current) is about 20—25 milliamperes. For a triode of high μ value, the saturation current is smaller, in some cases less than even one milliampere.

3. Valve constants, such as amplification factor, plate resistance (internal resistance of the valve) and mutual conductance, can all be determined from the same experimental set up. We have indicated how μ may be determined.

Oral questions

1. Describe the construction of a triode valve.
2. State the function of the filament, the grid and the plate.
3. Distinguish between the filament-type and the heater-type cathode. What is the advantage of the latter over the former ? How would you distinguish between two triodes having these two types of cathode ?
4. What is space charge ? Saturation current ? Will there be space charge if the current is at saturation ?
5. What is the direction of current flow within the valve ?
6. Define amplification factor.
7. Why don't you use the bias voltage from the power supply ?

Answers.

1 and 2. See Sec. 10-3.

3. Tungsten, thoriated tungsten or oxide coated emitters can be used for directly heated filaments. The heating current is passed directly through a filament of the material. In heater-type cathodes the heating current is applied to a separate *heater element*, located inside a cylindrical sleeve, which is the cathode. This sleeve is coated on the outside with the emitting material.

The heater-type cathodes are oxide-coated and can be operated at low temperatures (about 700° – 850°C). No voltage fluctuation of the heating system affects the grid or plate voltages.

A filament-type heater has *four* effective pins externally—one for the plate, one for the grid and two for the heating battery. A heater-type has *five* effective pins—four as above and another for the cathode which is insulated from the filament.

4. See Sec. 20 – 2 (portion marked 'Action')

5. Since electrons move from the cathode to the plate the conventional positive current flows from the plate to the cathode (anode to cathode) within the valve.

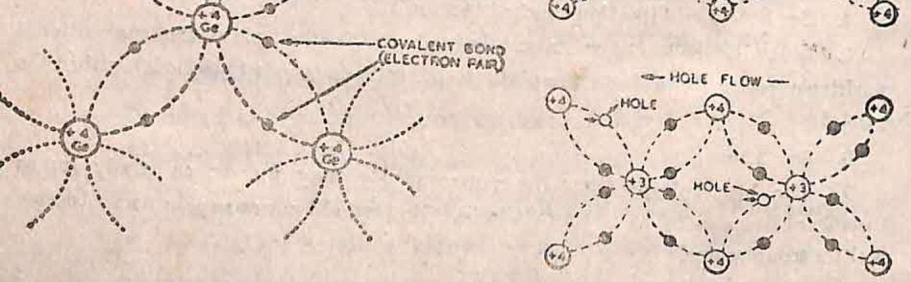
6. See 'Theory'.

7. The bias voltage from the power supply may not be as steady and as capable of fine control as we want it to be. Besides, old power supplies may become a little troublesome.

10-8. Impurity semiconductors and their action.

Semiconductors owe their moderate conductivity to the relatively few free electrons they contain compared with metals. There are many varieties of semiconductors. The type known as *impurity semiconductors* is widely used in electronics and transistor manufactures. The basic materials are garmanium and **silicon.** To understand their actions as impurity semiconductors we should have some idea of their atomic structure. Both have the same crystal structure and similar characteristics. For our purpose, what applies to one also applies to the other. So, we illustrate with germanium.

Germanium has *four* electrons in its outermost shell. These electrons are called **valence electrons.** They are easily dislodged to become electric current carries. For our purposes, the atom may be pictured as containing only these four electrons and four protons in the nucleus to keep it electrically neutral. When germanium is in the form of a crystal, adjacent germanium atoms share their valence electrons in a strong bond, so that effectively *four orbital* electron pairs *are associated with each nucleus.* These electron pairs are called **covalent bonds.** They are bound so strongly to each other and to the germanium nucleus that no free electrons are normally available to conduct a current through the germanium. A pure germanium crystal is practically a non-conductor of electricity. But heat energy occasionally breaks



Bond diagrams

Fig. 10.12(a) Covalent bonds in germanium.

Fig. 10.12(b) Bonds in N-type germanium.

Fig. 10.12(c) Bonds in P-type germanium.

some of these covalent bonds, thus liberating free electrons as charge carriers.

Fig. 10.12(a) shows the covalent bonds in a germanium crystal. (Remember silicon can be treated exactly in the same way.)

If a small amount of impurity is introduced into the germanium crystal, its current conducting characteristics change greatly. Thus when atoms that have five electrons in their outer shell (such as antimony or arsenic), are introduced into the germanium crystal (a process known as **doping**), the fifth electron of the impurity atom does not find a place in the symmetrical covalent bond structure. It moves about freely through the crystal. Such electrons are available as current carriers. Relatively few impurity or "donor" atoms within the germanium structure are enough to give rise to a substantial electron current when a voltage is applied [Fig. 10.12(b)].

Germanium that has been doped with pentavalent donor atoms is known as **N-type** germanium, because current is carried by *negative charge carriers* (electrons).

P-type germanium. If the impurity has **three electrons in** its outer shell (as in gallium, indium, boron, etc.) one of the covalent bonds around each such impurity atom has an electron ***missing***. This missing electron is called a **hole**. The hole behaves like a real **positively charged particle** when an electric field is applied across the crystal, and carries current from the positive to the negative terminal.

Germanium that has been doped with trivalent (acceptor) impurity is called **P-type** germanium. 'P' emphasizes that current is conducted by holes which act as **positive** charges. (Some electron conduction due to electrons freed by thermal agition will also be present, Fig 10.12(c)).

Minority carriers. Absorption of heat or light energy normally breaks some bonds in N-type germanium, giving rise to a number of holes. However, the electrons released by the arsenic impurity are, by far, the principal conductors of electricity in N-type germanium. For the same reason, free electrons exist in

P-type germanium. But it is the holes created by the trivalent impurity that account for the major portion of the electrical conduction that takes place.

It is thus seen that most part of the current is carried in N-type semiconductors by electrons, and a small parts by holes. On the other hand, holes carry most of the current in P-type semiconductors, and electrons carry a small part. The current carriers which carry the smaller part of the current are called **minority carriers.** In the N-type, they are holes, and in the P-type, they are electrons.

A piece of N or *P*-type semiconductor is electrically neutral.

Though additional free electrons are supplied to the germanium crystal by the 'donor' (pentavalent) atoms, do not think that the doped crystal is negatively charged. *It is electrically neutral.* If *n* pentavalent atoms are added to a crystal it contributes *n* free electrons to the crystal which carry the current. But this leaves the nucleus of a donor atom with an extra unit of positive charge that is, a proton whose charge is not neutralized by an electron in the atom. *n* donor atoms contribute *n* units of negative charge for conduction and retain *n* protons in the nucleus whose charge is not neutralized by electrons attached to these atoms. Looked from another angle, one may say that the addition of neutral donor atoms to the neutral germanium crystal does not give the crystal as excess of charge of any kind. The same applies to P-type semiconductors.

10-9. The semiconductor diode. A P-N junction diode is a semiconductor crystal of which one part is P-type and the rest N-type. Suppose a potential difference is applied across a P-N junction diode, making the P-end positive and the N-end negative. Application of such p. d. is known as **forward biasing.** In such a case the holes will be repelled toward the negative end and the electrons, toward the positive end. A current will thus flow across the junction. But if the connections are reversed, making the P-end negative and the N-end positive, the holes will remain attracted toward the negative end and the electrons, toward the positive end. Hence no current will flow across the junction in this case. This is known as **reverse biasing.**

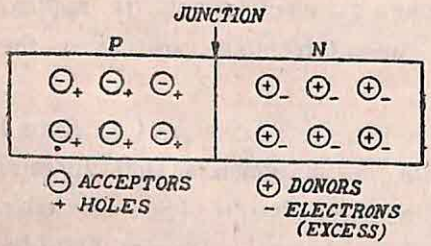
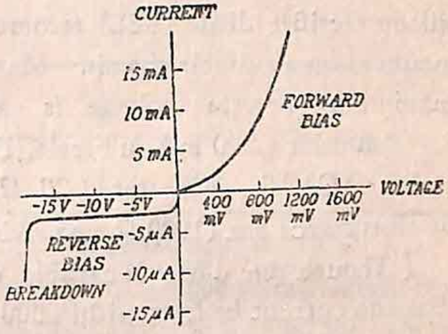


Fig. 10.13 (P-N junction diode)

A P-N junction therefore allows a current to pass through it when it has a forward bias. But no current passes when it has a negative bias. A junction diode serves as a rectifier in this way.

The typical current voltage characteristic for a semiconductor diode is shown in Fig. 10.14 Both forward and reverse characteristics are given in the data provided by the makers. In the forward direction the current increases roughly exponentially with voltage. But in the reverse direction a small saturation current is reached when the applied voltage is very small. This current remains practically constant as the voltage is increased. If the reverse voltage becomes too large, the device first breaks down and becomes a short circuit, after which it may burn out and become an open circuit.



Fig, 10.14

[The junction diode we recommend for this experiment is type BY 127, manufactured by BEL in this country. It is a silicon rectifier diode with a maximum reverse voltage of 1250V, and can carry a current of 1 amp. A diagram showing its side (together with the semiconductor diode symbol) is give in Fig. 10.15.]

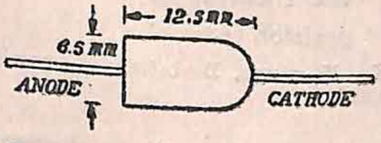


Fig. 10.15

10-10. To draw the characteristic curve of a junction diode.

Theory. A p-n junction diode allows a current to pass through it when its p-end is made positive and n-end negative. On reversal of the polarities practically no current passes through the junction. The diode can thus act as a rectfier of alternating current. (If the reverse bias is very high the action breaks down.)

The relation between the applied voltage V and the current flowing through the junction is called the characteristic curve of the diode.

List of apparatus. 1. The junction diode under test [BY 127 silicon rectifier diode (BEL) recommended for use. It should be mounted on a suitable chassis. Maximum current is 1 A, and the maximum reverse voltage is 1250 V.] 2. 9-volt battery. 3. Ammeter (500 mA full-scale, D. C.). 4. Voltmeter (3 V full-scale, D.C.) 5. Rheostat (20 Ω, 600 mA max. will do). 6. Resistance box (1000 Ω max. will do). 7. Two key.

[Though the diode is capable of carrying 1 A, it is desirable that the current be kapt within 500 mA in the experiment.]

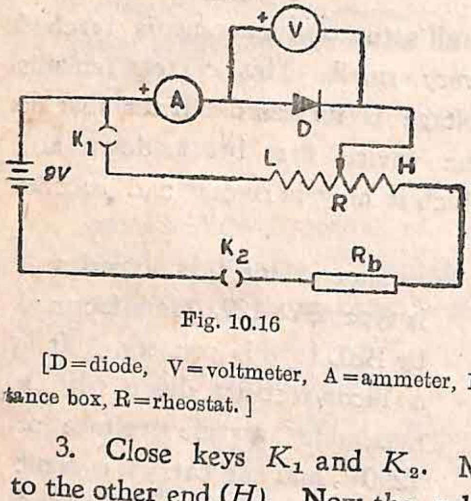


Fig. 10.16

[D=diode, V=voltmeter, A=ammeter, K_1, K_2=keys, B=battery, R_b=resistance box, R=rheostat.]

Instructions. 1. Connect the components as shown in the circuit diagram (Fig. 10. 16). Check the connections carefully.

2. Open the plug for 30Ω in the resistance box R_b and bring the slider of the rheostat to the lowest position (L).

3. Close keys K_1 and K_2. Move the slider of the rheostat to the other end (H). Now the voltmeter will record an increasing voltage across the diode.

4. Take readings of voltage and current for each 0·1V increase in voltage. (Up to about 0·5V the current will be negligible.) When the voltage across the diode exceeds 0·7V (at this voltage the diode will start conducting), open the key K_1 and readjust R and R_b so as to give 0·8V across the diode.

5. Have the key K_2 closed only when you are taking readings or adjusting the voltage. Otherwise the battery current

will be drawn unnecessarily and the diode will be heated.

6. Record data as follows, plot the points and draw the graph.

Experimental results :

Junction diode No.……

Applied voltage (V)							
Observed current (I) in mA							

Draw the V-I graph. This is the required characteristic.

Note. Necessity of the key K_1. When the voltage across the diode is small ($0{\cdot}7V$ in the case of silicon and $0{\cdot}3V$ in the case of germanium diodes), the diode acts an open circuit (that is, no current passes). If we want to apply a small voltage (below the above values) across the diode, there should be a shunt across the diode to which this small voltage is applied. This purpose is served by putting the key K_1 in the circuit. Otherwise the voltage across the diode cannot be varied by varying the series resistance only.

Oral questions

1. What are the following : (i) semiconductor. (ii) intrinsic semiconductor, (iii) impurity semiconductor ?

What is the most characteristic difference between a conductor and a semiconductor ?

2. What are P-type and N-type semiconductors ? Are they electrically charged ?

3. What is a P-N juuction ? A P-N diode ?

4. What do you understand by forward biasing and reverse biasing of a semiconductor diode ?

5. What may happen if you give a semiconductor diode a large reverse bias ?

Answers.

1. See Sec. 10-5. An intrinsic semiconductor is a pure solid which has an appreciable electrical conductivity at the room temperature which increases rapidly with rise of temperature.

In metallic conductors, the electrical conductivity diminishes with rise of temperature, conduction being due to free electrons alone. In semiconductors, electrical conductivity increases with rise of temperature. Conduction is due to electrons and holes.

2. See Sec. 10-8.

3. A semiconductor, one portion of which is P-type, and the rest N-type is a P-N diode. The place where the two types of material are in :contact is a P-N junction.

4. See para 1, Sec. 10-9.

5. See para 3, Sec. 10-9.

10-11. Transistors. A transistor is a semiconductor device capable of amplification in a manner similar to thermionic valves. It consists of two P-N semiconductor junctions placed back to back, forming either a P-N-P or N-P-N structure. The central region in both types is very thin. In a P-N-P transistor, the central N-region is called the **base**, one P-region is called the **emitter**, and the other the **collector**. The emitter-base P-N junction is forward biased ; the base-collector junction is reverse biased. In an N-P-N transistor the P-region is the base, one of the N-regions is the emitter and the other the collector. Here also the emitter-base N-P junction is forward biased ; the other juction is reverse biased.

The collector of a transistor corresponds to the anode of a thermionic valve ; the emitter corresponds to the cathode. The base is analogous to the control grid.

With proper biasing of the two junctions in an N-P-N transistor, a large number of electrons in the emitter region are attracted to the base P-layer. If this layer is sufficiently thin, it will allow most of the electrons to pass through it, only a small percentage combining with the holes in the P-layer. The rest will be attracted into the positive collector. The magnitude of the collector current will depend on the extent of the positive bias on the P-layer base. By suitable design, the device can be made to give collector current many (say, 20-100 or so) times the base current. The ratio of the collector current to the base current is the *current gain* of the transistor.

A P-N-P transistor acts in an exactly similar manner with the difference that the current carriers are *holes* instead of electrons.

The *advantages* of a transistor over a valve are (i) that it is much less bulky and fragile, (ii) that it requires no heater current and (iii) that the voltage at the collector need only be a few volts.

10-11.1 The common-emitter type of connection. When transistors are operated as amplifiers, three different basic circuit connections are possible. One of these is known as the *common-emitter type*, and is the most flexible and efficient of the three basic connections. It has the highest voltage and power gain of the three circuits.

The type of connection can be seen in Fig.s 10.20 and 10.21.

10-11.2 Transistor characteristic curves. The performance of transistors may be determined from characteristic curves of their voltage and current relations, just as for the triodes. In the experiment described in Sec. 10.12, we draw what we call *collector characteristics* (or output characteristics), the connections being of the common-emitter type.

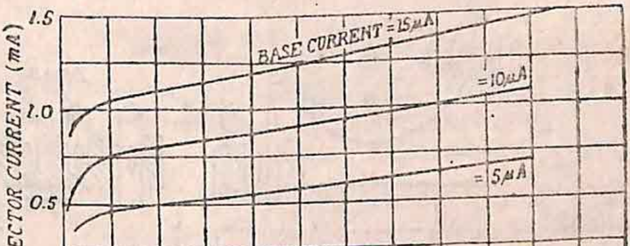


Fig. 10.17

(Nature of collector characteristics of a pnp transistor)

Such a characteristic curve is a plot of the collector current (I_C) against collector-emitter voltage (V_{CE}) for a given base current (I_B). This corresponds to $I_a - V_a$ curve at constant V_g for a triode. When such curves are drawn for different base currents, we get a family of collector characteristics. Their nature is shown in Fig. 10.17.

There are other forms of characteristic curves, as for triodes.

10-11.3. Transistor to be used and the internal chassis arrangement for our experiment.

For our work, we shall choose type AC 127 or AC 128 transistor manufactured by BEL. The former is N-P-N and the latter a P-N-P transistor. Their size and symbols are shown in Fig 10.18. The internal arrangement of the chassis is given in the next figure (Fig. 10.19).

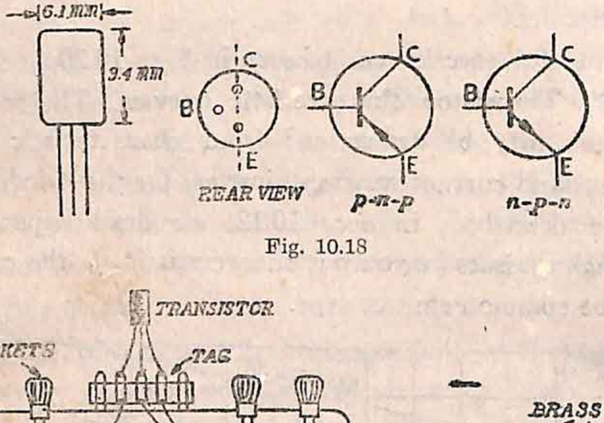


Fig. 10.18

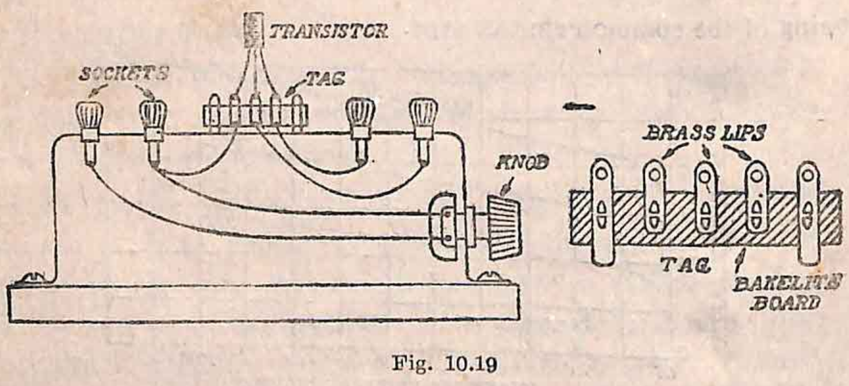


Fig. 10.19

10.12. To study the collector characteristics of a transistor in the C-E (common-emitter) mode

Theory. The purpose of the study is to observe the variation of collector current with the collector-emitter voltage at different base currents, and to represent the results in the form of graphs, called *characteristics*.

List of apparatus. 1. The transistor under study. [Type AC 128 or AC 127 (BEL) is recommended. The first is a pnp and the second an npn germanium alloy transistor.]

2. Ammeters (100 μA or 500 μA full-scale, and 10 mA full scale).
3. Voltmeter (10 V full-scale, with at least 10 k Ω per volt).
4. Carbon potentiometer (1 megohm, linear).
5. Rheostat (500 Ω, 0·6 A).
6. Resistance box (50 Ω max).
7. Batteries (9V, 6×1·5 V) and 1·5 V.
8. Keys.

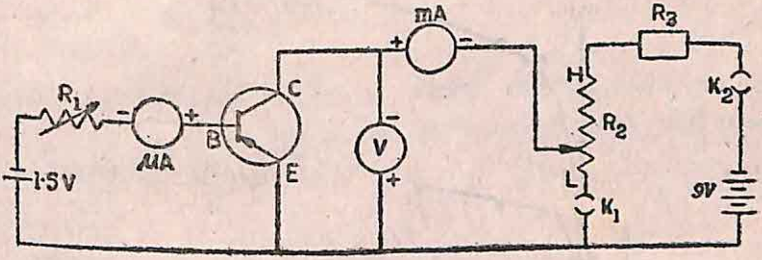


Fig. 10.20 (p-n-p)

[R_1 = carbon potentiometer ; R_2 = rheostat ; R_3 = resistance box ; B = base, C = collector, E = emitter ; μA = microammeter ; mA = milliammeter.]

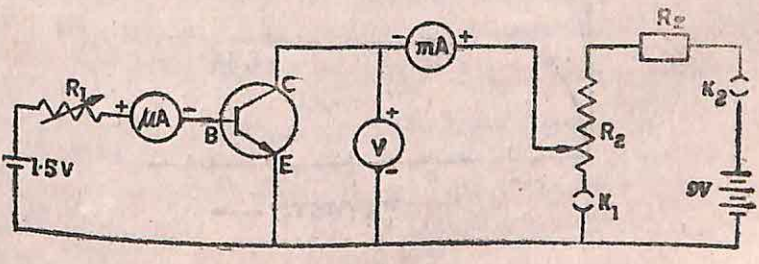


Fig. 10,21 (p-n-p)

Instructions. 1. Connect the components as shown in the circuit diagram. Check the connections carefully.

2. Adjust the carbon potentiometer (R_1) to set the base current at 10 μA.

3. Put 30 Ω in the resistance box (R_3). Keep the slider of the rheostat (R_2) at the minimum resistance position (L).

4. Close the keys K_1 and K_2. Adjust the slider of the rheostat (R_2) to apply voltage across the collector and the emitter.

5. Note down the readings for collector current (I_C) and collector-emitter voltage (V_{CE}). Initially (up to 0·5 V) readings should be taken at 0·25V intervals. Afterwards, readings at 0·5 V intervals will do.

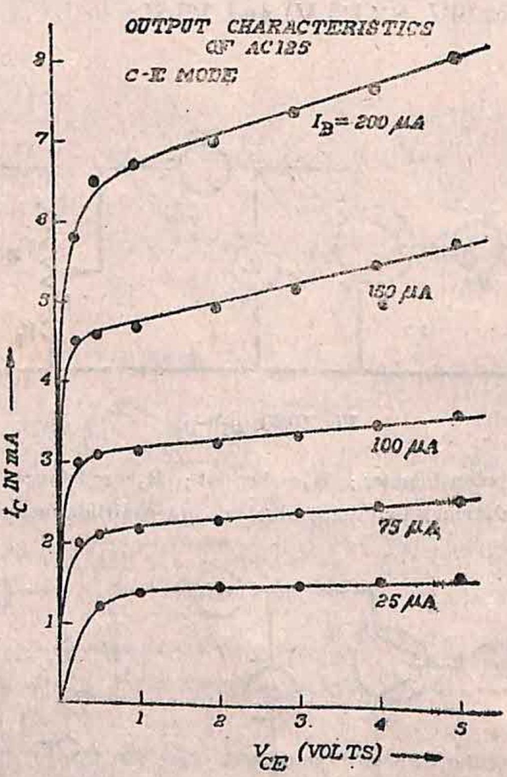


Fig. 10.22

6. Open the key K_1 after 0·5 V and readjust for higher voltage (because the voltage distribution alters a little as you go up).

7. Check the base current before each reading and readjust R_1 to keep the base current at a fixed value for a particular set of readings.

8. Take different sets of readings at different base currents (for example, 10 μA, 20 μA, 25 μA, 30 μA etc). Do not exceed, say, 200 μA.

Tabulate as follows

Experimental results.

I. *Base current*$=\cdots\mu$A

V_{CE}(in V)						etc.
I_C (in mA)						etc.

II. *Base current*$=\cdots\mu$A

Similarly for other base currents. Draw the relevant graphs on the same paper. The nature of the curves for a particular transistor is shown in Fig. 10.22.

Oral questions

1. What is a transistor ? Describe any one type.
2. Distinguish between P-N-P and N-P-N types.
3. What is meant by *emtter*,; *base* and *collector* of a transistor ? What are their corresponding parts in a triode valve ?
4. What are the broad advantages of a transistor over a triode ?
5. What is meant by the common-emitter type of connection ?
6. What is meant by a transistor characteristic ?
7. What is *current gain* in a transistor ?
8. Explain the symbols you have used in the circuit diagram.

Answers. 1 to 4. (See Sec. 10.11)

5. (See Sec. 10-11.1)
6. (See Sec. 10-11.2)
7. *Current gain* of a transistor is the ratio of the collector current to the base current.
8. (If necessary, check from earlier diagrams.)

TABLES

Densities of common substances

(in g/cm³)

Substance	Density	Substance	Density	Substance	De
Solids		Naphthalene	1·15	Spirit	
Aluminium	2·70	Nickel	8·8	Milk	
Alum (Potassium)	1·76	Paraffin	0·87-0·93	Olive oil	0·9
Brass	8·4-8·7	Porcelain	2·2-2·4	Paraffin oil	
Carbon (Graphite)	2·3	Quartz	2·66	Sea-water	1·0
Copper	8·93	NaCl	2·17	Turpentine	
Cork	0·22-0·26	Sand	2·63		
German-silver	8·3-8·9	Silver	10·5	Gases	
Gold	19·32	Steel	7·7-7·9	(at S.T.P.)	
Glass (Crown)	2·5-2·7	Sugar	1·59	Air	0·00
Glass (Flint)	2·9-4·5			Ammonia	0·00
Glass (Pyrex)	2·25	**Liquids**		Carbondioxide	0·00
Iron (Cast)	7·0-7·7	Alcohol (Ethyl)	0·792	Helium	0·00
Iron (Wrought)	7·8-7·9	Chloroform	1·527	Hydrogen	0·00
Lead	11·37	Glycerine	1·26	Nitrogen	0·00
Marble	2·5-2·8	Kerosene	0·80	Oxygen	0·00
		Mercury	13·6	Steam (at 100°C)	0·001

Breaking stresses of common laboratory materials

(in kgf/cm²)

Brass ...	3160 to 3980	Iron (annealed) ...	4700
Copper (hard drawn)...	4080 to 4700	Steel (ordinary) ...	11230
,, (annealed) ...	2860 to 3160		
Iron (hard drawn) ...	5510 to 6330	,, (tempe	15810
		,, (pianoforte) ...	18980 to 237

Density of water

(in g/cm³)

Temp. in °C	0	2	4	6	8
0	0·99987	0·99997	1·0000	0·99997	0·99988
10	·99973	·99953	·99927	·99897	·99862
20	·99823	·99780	·99732	·99681	·99626
30	·99567	·99505	·99440	·99371	·9930
40	·9922	·9915	·9907	·9898	·9890
50	·9881	·9872	·9862	·9853	·9843
60	·9832	·9822	·9811	·9801	·9789
70	·9778	·9767	·9755	·9743	·9731
80	·9718	·9706	·9693	·9680	·9667
90	·9653	·9640	·9626	·9612	·9598

Elastic constants

ubstance	Young's modulus (E) in dynes per cm².	Bulk modulus (K) in dynes per cm².	Rigidity modulus (G) in dynes per cm².	Poisson's ratio (σ)
	$\times 10^{11}$	$\times 10^{11}$	$\times 10^{11}$	
uminium	7·05	7·46	2·67	0·34
ass	9·7-10·2	10·65	3·5	0·34-0·40
pper	12·4-12·9	14·3	3·9-4	0·26
n (Cast)	10-13	9·6	3·5-5·3	0·23-0·31
n Vrought)	19-20	14·6	7·7-8·3	0·27
el	19·5 20·6	18·1	7·9-8·9	0·25-0·33
rtz	5·18	1·4	3·0	—
ber lcanized)	0·10-0·70	—	0·00016	0·46-0·49

Saturation vapour pressure of water

Temp. in °C	Pressure in mm Hg	Temp. in °C	Pressure in mm Hg	Temp. in °C	Pressure in mm Hg	Temp. in °C	Pressure in mm Hg
		6	7·011	22	19·79	50	92·30
		7	7·511	23	21·02	55	117·9
		8	8·042	24	22·32	60	149·2
		9	8·606	25	23·69	65	187·3
		10	9·205	26	25·13	70	233·5
		11	9·840	27	26·65	75	288·9
		12	10·513	28	28·25	80	355·1
		13	11·226	29	29·94	85	433·4
−2	3·96	14	11·980	30	31·71	90	525·8
−1	4·26	15	12·779	31	33·57	95	633·9
0	4·58	16	13·624	32	35·53	100	760·0
1	4·924	17	14·517	33	37·59	120	1489
2	5·290	18	15·460	34	39·75	140	2709
3	5·681	19	16·456	35	42·02	160	4633
4	6·097	20	17·51	40	55·13	180	7514
5	6·541	21	18·62	45	71·54	200	11647

Coefficients of linear expansion

Solids	Coefficient of linear expansion per °C	Solids	Coefficient o linear expans per °C
	$\times 10^{-6}$		×1
Aluminium	25·5	Invar steel (With 36% Ni)	0·9
Brass	18·9	Invar (other varieties)	−0·3 to 2
Constantan	17·0	Lead	29·1
Copper	16·7	Nickel	12·8
Fused Silica	0·6	Quartz (fibre)	1·7
Glass (Flint)	7·8	Zinc	25·8-26·
Glass (Crown)	9·0	German-silver	18·4
Glass (Pyrex)	0·3		
Ice	50·7		
Iron (Cast)	10·2		
Iron(Wrought)	11·9		

Specific heats of solids and liquids (cal/g °c)

Substance	Temp. in °C	Specific heat	Substance	Temp. in °C	Specific heat
Solids :					
Aluminium	0	0·2096	Paraffin wax	0-20	0·69
Brass	0	0·089	Porcelain	15-200	0·18
Constantan	18	0·098	Sand	20-100	0·19
Copper	0	0·0909	Zinc	0	0·0918
German silver	0-100	0·095	**Liquids :**		
Glass (Flint)	10-15	0·12	Alcohol (Ethyl)	0	0·547
Glass (Crown)	10-15	0·16	Aniline	15	0·514
Granite	20-100	0·19-·20	Glycerine	18-50	0·58
Ice	−21 to −1	0·502	Castor oil	20	0·508
Iron	0	0·1045	Linseed oil	20	0·44
Lead	0	0·0302	Olive oil	7	0·47
Marble	18	0·21-0·22	Paraffin oil	20-60	0·51-0·54
NaCl	10	0·21	Mercury	0	0·0335
Nickel	0	0·106	Turpentine	18	0·42

Acceleration due to gravity (g) and horizontal intensity of earth's magnetic field (H) at different places in India

Place	'*g*' in cm/s²	'*H*' in oersted	Place	'*g*' in cm/s²	'*H*' in oersted
Agra	979·0	0·347	Delhi	979·2	0·341
Ajmere	978·9	0·346	Hyderabad (Deccan)	978·9	0·379
Allahabad	979·0	0·358	Lucknow	979·0	0·385
Bangalore	978·0	0·381	Madras	978·3	0·369
Bombay	978·6	0·365	Mysore	978·0	0·380
Calcutta	978·8	0·374	Nagpur	978·5	0·368
Cuttack	978·7	0·377	Patna		0·360

Normal boiling points of liquids

Liquid	Boiling point in °C	Liquid	Boiling point in °C
Acetone	56·5	Chloroform	61·2
Aniline	183·9	Ethyl acetate	77·1
Benzene	80·2	Ethyl alcohol	78·3
Carbon disulphide	46·2	Methyl alcohol	64·7
Carbon tetrachloride	76·7	Methyl acetate	57·1

Melting points of solids

Solid	Melting point in °C	Solid	Melting point in °C
Chloracetic acid	63	Phenol	42·7
Diphenylamine	54	Phenyl acetic acid	76·5
Indol	52	Potash alum	84·5
Naphthalene	80	Stearic acid	69·3
Palmitic acid	62·6	Thymol	50
		Trichloracetic acid	57·5

Mean coefficients of cubical expansion of liquids (γ)

(for a range around 18°C unless otherwise stated)

Liquid	γ per °C	Liquid	γ per °C
Glycerine	53×10^{-5}	Turpentine	94×10^{-5}
Mercury	$18{\cdot}1\times10^{-5}$		
Olive oil	70×10^{-5}	Water (20°-40°)	$30{\cdot}2\times10^{-5}$
Paraffin oil	90×10^{-5}	Water (40°-60°)	$45{\cdot}8\times10^{-5}$
Paraffin oil (20°-199°C)	110×10^{-5}	Water (60°-80°)	$58{\cdot}7\times10^{-5}$

Thermal conductivities

(in cal cm^{-1} s^{-1} $°C^{-1}$)

Substance	Temp. in °C	Thermal conductivity	Substance	Temp. in °C	Thermal conductivity
Aluminium	18	0·480			
Asbestos	...	3×10^{-4}	Iron (Wrought)	18	0·144
Asbestos paper	...	6×10^{-4}			
Brass	17	0·260	Marble (Whole)	...	$7·1 \times 10^{-3}$
Constantan	18	0·054	Mica	...	$1·8 \times 10^{-3}$
Copper	18	0·918	Paper	...	$0·3 \times 10^{-3}$
Ebonite	...	$4·2 \times 10^{-4}$	Porcelain	...	$2·5 \times 10^{-3}$
German-silver	18	0·070	Rubber	...	0·45×10
Glass (Crown)	...	0·0025	Steel	18	0·108
Glass (Flint)	...	0·002	Nickel	18	0·142
Iron (Pure)	100	0·176	Silver	18	1·006
Iron (Cast)	54	0·114	Zinc	18	0·265

Refractive indices of substances

[with respect to air for Na-D line (5893×10^{-8} cm)]

Solids	Refractive index	Solids	Refractive index	Liquids	Refractive index
Glass (Crown)	1·48-1·61	Felspar	1·52	Water	1·3330
		Fluorite	1·4339	Alcohol (Ethyl)	1·362
Glass (Flint)	1·53-1·96	Mica	1·56-1·60		
Alum	1·456	Quartz Ord. ray)	1·5443	Canada-balsam	1·53
Calcspar (Ord. ray)	1·5584	Quartz (Ext. ray)	1·5534	Cedar oil	1·516
Calcspar (Ext. ray)	1·4864	Rock salt	1·544	Glycerine	1·47
Diamond	2·417	Sylvine	1·4904	Paraffin oil	1·44
Ice	1·31	Ruby	1·76	Olive oil	1·46

Wavelengths of bright spectral lines

Substance	Colour	Wave-length in Å	Substance	Colour	Wave length in Å
	Yellow (D_2)	5890	Helium	Violet	3889
	,, (D_1)	5896		,,	4026
Potassium	Red	7668		Blue	4471
	,,	7702		,,	4713
Argon	Blue	4703		Greenish blue	4922
	Green	5452		Green	5016
	Yellow	5607		Yellow (D_3)	5876
	,,	5912		Red	6678
	Orange	6031 (strongest)		,,	7065
	,,	6059	Hydrogen	Blue (γ)	4340
				Greenish bule (β)	4861
				Red (α)	5853
				Yellow	6563

1°A. $= 10^{-8}$ cm.

Specific resistances and temperature coefficients of resistance

Substance	Specific resistance in ohm. cm at 18°C	Temp. coefficient of resistance per °C	Substance	Specific resistance in ohm. cm at 18°C	Temp. coefficient of resistance per °C
	$\times 10^{-6}$	$\times 10^{-4}$		$\times 10^{-6}$	$\times 10^{-4}$
Aluminium	3·21	38	Iron (Wrought)	13·9	62
Antimony	40·5	—39·8	Lead	20·8	43
Bismuth	119·0	42	Manganin	44·5	0·02-0·5
Brass	6-9	10	Mica	9×10^{21}	
Carbon lamp filament	4000		Nickel	11·8	27
Cobalt	9·7	33	Nichrome	110	1·7
Constantan	49·0	0·4 to +0·1	Phosphor-bronze	5-10	
Copper	1·78	42·8	Platinoid	34·4	2·5
German-silver	16-40	2·3-6	Platinum	11·0	37
Glass (conducting)	5×10^{14}		Quartz	$1{\cdot}2\times 10^{20}$	
			Silver	1·63	40
Glass (other varieties)	$>10^{20}$		Steel	19·9	16-42
			Zinc	6·1	37
			Gold	2·42	40
Iron (Cast)	74-98		Graphite	3000	—5·6 to 8·8

E M. F. of cells

Cell	E.m.f. in volts	Cell	E.m.f. in volts
Daniell	1·07-1·08	Cadmium (Weston)	1·01830 (at 20°C)
Leclanche	1·5	*Secondary* :	
Standard :		Lead acid cell	1·9-2·2
Clark	1·433 (at 15°C)	Nickel-Iron alkali cell	1·1-1·4

Electrochemical equivalent

Element	Chemical equivalent	E.C.E. (in gram/coulomb)
Silver	107·88/1	0·00111800
Copper	63·57/2	0·0003294
Hydrogen	1·008/1	0·000010447

E.M.F. of common thermo-couples

Values of *a* and *b* in the equation $E=at+bt^2$ when one junction of the couple is at 0°C and the other at t°C.

Couple	*a*	*b*
Copper-constantan	$37{\cdot}54\times10^{-6}$	$0{\cdot}0445\times10^{-6}$
Copper-iron	$13{\cdot}40\times10^{-6}$	$-0{\cdot}0137\times10^{-6}$

As *a* and *b* vary considerably in different commercial specimens, the values given above should be regarded as approximate.

LOGARITHMS

	0	1	2	3	4	5	6	7	8	9	Mean Differences								
											1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7824	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

Some useful logarithms

log $\pi = 0.4971$
log $76 = 1.8808$
log $273 = 2.4362$

log $980 = 2.9912$
log $13.6 = 1.1335$
log $4.2 = 0.6232$

LOGARITHMS

	0	1	2	3	4	5	6	7	8	9	Mean Differences								
											1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7038	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

Some useful constants

$\pi = 3.1416 = 3.142$

$\pi^2 = 9.8696 = 9.870$

$e = 2.71828........ = 2.718$

$\log_e 10 = 2.30258.... = 2.303$

$$e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \text{..........} \text{ to } \infty$$

ANTILOGARITHMS

	0	1	2	3	4	5	6	7	8	9	Mean Differences								
											1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1023	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	2
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	3
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1631	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1624	1828	1832	1837	1841	1845	1649	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

Conversion table

	Reciprocal		Reciprocal
1 inch = 2.54 cm	0.3937	1 lb = 453.6 gm	0.0022
1 yard = 0.9144 m	1.0936	= 0.4536 Kgm	2.2046
1 cu. ft. = 28.32 litres	0.03531	1 gallon = 4.546 litres	0.2200

ANTILOGARITHMS

	0	1	2	3	4	5	6	7	8	9	Mean Differences								
											1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3236	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

Conversion table (Contd.)

	Reciprocal
1 atmos. $=1.013\times10^6$ dynes/sq. cm.	9.873×10^{-7}
1 gm/c.c. $=62.43$ lb/cu. ft.	0.01602
1 radian $=57.3$ degrees	0.01745
1 calorie $=4.185$ joules	0.2389

$\log_e x=\log_e 10\times\log_{10}x=2.303\times\log_{10}x$

NATURAL TANGENTS

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Mean Differences				
											1′	2′	3′	4′	5′
0°	·0000	0017	0035	0052	0070	0087	0105	0122	0140	0157	3	6	9	12	15
1	·0175	0192	0209	0227	0244	0262	0279	0297	0314	0332	3	6	9	12	15
2	·0349	0367	0384	0402	0419	0437	0454	0472	0489	0507	3	6	9	12	15
3	·0524	0542	0559	0577	0594	0612	0629	0647	0664	0682	3	6	9	12	15
4	·0699	0717	0734	0752	0769	0787	0805	0822	0840	0857	3	6	9	12	15
5	·0875	0892	0910	0928	0945	0963	0981	0998	1016	1033	3	6	9	12	15
6	·1051	1069	1086	1104	1122	1139	1157	1175	1192	1210	3	6	9	12	15
7	·1228	1246	1263	1281	1299	1317	1334	1352	1370	1388	3	6	9	12	15
8	·1405	1423	1441	1459	1477	1495	1512	1530	1548	1566	3	6	9	12	15
9	·1584	1602	1620	1638	1655	1673	1691	1709	1727	1745	3	6	9	12	15
10°	·1763	1781	1799	1817	1835	1853	1871	1890	1908	1926	3	6	9	12	15
11	·1944	1962	1980	1998	2016	2035	2053	2071	2089	2107	3	6	9	12	15
12	·2126	2144	2162	2180	2199	2217	2235	2254	2272	2290	3	6	9	12	15
13	·2309	2327	2345	2364	2382	2401	2419	2438	2456	2475	3	6	9	12	15
14	·2493	2512	2530	2549	2568	2586	2605	2623	2642	2661	3	6	9	12	16
15	·2679	2698	2717	2736	2754	2773	2792	2811	2830	2849	3	6	9	13	16
16	·2867	2886	2905	2924	2943	2962	2981	3000	3019	3038	3	6	9	13	16
17	·3057	3076	3096	3115	3134	3153	3172	3101	3211	3230	3	6	10	13	16
18	·3249	3269	3288	3307	3327	3346	3365	3385	3404	3424	3	6	10	13	16
19	·3443	3463	3482	3502	3522	3541	3561	3581	3600	3620	3	7	10	13	16
20°	·3640	3659	3679	3699	3719	3739	3759	3779	3799	3819	3	7	10	13	17
21	·3839	3859	3879	3899	3919	3939	3959	3979	4000	4020	3	7	10	13	17
22	·4040	4061	4081	4101	4122	4142	4163	4183	4204	4224	3	7	10	14	17
23	·4245	4265	4286	4307	4327	4348	4369	4390	4411	4431	3	7	10	14	17
24	·4452	4473	4494	4515	4536	4557	4578	4599	4621	4642	4	7	11	14	18
25	·4663	4684	4706	4727	4748	4770	4791	4813	4834	4856	4	7	11	14	18
26	·4877	4899	4921	4942	4964	4986	5008	5029	5051	5073	4	7	11	15	18
27	·5095	5117	5139	5161	5184	5206	5228	5250	5272	5295	4	7	11	15	18
28	·5317	5340	5362	5884	5407	5430	5452	5475	5498	5520	4	8	11	15	19
29	·5543	5566	5589	5612	5635	5658	5681	5704	5727	5750	4	8	12	15	19
30°	·5774	5797	5820	5844	5867	5890	5914	5938	5961	5985	4	8	12	16	20
31	·6009	6032	6056	6080	6104	6128	6152	6176	6200	6224	4	8	12	16	20
32	·6249	6273	6297	6322	6346	6371	6395	6420	6445	6469	4	8	12	16	20
33	·6494	6519	6544	6569	6594	6619	6644	6669	6694	6720	4	8	13	17	21
34	·6745	6771	6796	6822	6847	6873	6899	6924	6950	6976	4	9	13	17	21
35	:7002	7028	7054	7080	7107	7133	7159	7186	7212	7239	4	9	13	18	22
36	·7265	7292	7819	7346	7373	7400	7427	7454	7431	7508	5	9	14	18	23
37	·7536	7563	7590	7618	7646	7673	7701	7729	7757	7785	5	9	14	18	23
38	·7813	7841	7869	7898	7926	7954	7983	8012	8040	8069	5	9	14	19	24
39	·8098	8127	8156	8185	8214	8243	8273	8302	8332	8361	5	10	15	20	24
40°	·8391	8421	8451	8481	8511	8541	8571	8601	8632	8662	5	10	15	20	25
41	·8693	8724	8754	8785	8816	8847	8878	8910	8941	8972	5	10	16	21	26
42	·9004	9036	9067	9099	9131	9163	9195	9228	9260	9293	5	11	16	21	27
43	·9325	9358	9391	9424	9457	9490	9523	9556	9590	9623	6	11	17	22	28
44	·9657	9691	9725	9759	9793	9827	9861	9896	9930	9965	6	11	17	23	29

Electrical Units

1 ampere $=\frac{1}{10}$ e.m.u. $=3\times10^9$ e.s.u.

1 coulomb $=\frac{1}{10}$ e.m.u. 0×10^9 e.s.u.

1 volt $=10^8$ e.m.u. $=\frac{1}{300}$ e.s.u.

NATURAL TANGENTS

	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′	Mean Differences				
											1′	2′	3′	4′	5′
45°	1·0000	0035	0070	0105	0141	0176	0212	0247	0283	0319	6	12	18	24	30
46	1·0355	0392	0428	0464	0501	0538	0575	0612	0649	0686	6	12	18	25	31
47	1·0724	0761	0799	0837	0875	0913	0951	0990	1028	1067	6	13	19	25	32
48	1·1106	1145	1184	1224	1263	1303	1343	1383	1423	1463	7	13	20	27	33
49	1·1504	1544	1585	1626	1667	1708	1750	1792	1833	1875	7	14	21	28	34
50°	1·1918	1960	2002	2045	2088	2131	2174	2218	2261	2305	7	14	22	29	36
51	1·2349	2393	2437	2482	2527	2572	2617	2662	2708	2753	8	15	23	30	38
52	1·2799	2846	2892	2938	2985	3032	3079	3127	3175	3222	8	16	24	31	39
53	1·3270	3319	3367	3416	8465	3514	3564	3613	3663	3713	8	16	25	33	41
54	1·3764	3814	3865	3016	3968	4019	4071	4124	4176	4229	9	17	26	34	43
55	1·4281	4335	4388	4442	4496	4550	4605	4659	4715	4770	9	18	27	36	45
56	1·4826	4882	4938	4994	5051	5108	5166	5224	5282	5340	10	19	29	38	48
57	1·5399	5458	5517	5577	5637	5697	5757	5818	5880	5941	10	20	30	40	50
58	1·6003	6066	6128	6191	6255	6319	6383	6447	6512	6577	11	21	32	43	53
59	1·6643	6709	6775	6842	6909	6977	7045	7113	7182	7251	11	23	34	45	56
60°	1·7321	7391	7461	7532	7603	7675	7747	7820	7893	7966	12	24	36	48	60
61	1·8040	8115	8190	8265	8341	8418	8495	8572	8650	8728	13	26	38	51	64
62	1·8807	8887	8967	9047	9128	9210	9292	9375	9458	9542	14	27	41	55	68
63	1·9626	9711	9797	9883	9970	$\bar{0}057$	$\bar{0}145$	$\bar{0}233$	$\bar{0}323$	$\bar{0}413$	15	29	44	58	73
64	2·0503	0594	0686	0778	0872	0965	1060	1155	1251	1348	16	31	47	63	78
65	2·1445	1543	1642	1742	1842	1943	2045	2148	2251	2355	17	34	51	68	85
66	2·2460	2566	2673	2781	2889	2998	3109	3220	3332	3445	18	37	55	73	92
67	2·3559	3673	3789	3906	4023	4142	4262	4383	4504	4627	20	40	60	79	99
68	2·4751	4876	5002	5129	5257	5386	5517	5649	5782	5916	22	43	65	87	108
69	2·6051	6187	6325	6464	6605	6746	6889	7034	7179	7326	24	47	71	95	119
70°	2·7475	7625	7776	7929	8083	8239	8397	8556	8716	8878	26	52	78	104	131
71	2·9042	9208	9375	9544	9714	9887	$\bar{0}061$	$\bar{0}237$	$\bar{0}415$	$\bar{0}595$	29	58	87	116	145
72	3·0777	0961	1146	1334	1524	1716	1910	2106	2305	2506	32	64	96	129	161
73	3·2709	2914	3122	3332	3544	3759	3977	4197	4420	4646	36	72	108	144	180
74	3·4874	5105	5339	5576	5816	6059	6305	6554	6806	7062	41	81	122	163	204
75	8·7321	7583	7848	8118	8391	8667	8947	9232	9520	9812	46	93	139	186	232
76	4·0108	0408	0713	1022	1335	1653	1976	2303	2635	2972					
77	4·3315	3662	4015	4374	4737	5107	5483	5864	6252	6646					
78	4·7046	7453	7867	8288	8716	9152	9594	$\bar{0}045$	$\bar{0}504$	$\bar{0}970$					
79	5·1446	1929	2422	2924	3435	3955	4486	5026	5578	6140					
80°	5·6713	7297	7894	8502	9124	9758	$\bar{0}405$	$\bar{1}066$	$\bar{1}742$	2432					
81	6·3138	3859	4596	5350	6122	6912	7720	8548	9395	$\bar{0}264$	*Mean* differences no longer sufficiently accurate.				
82	7·1154	2066	3002	3962	4947	5958	6996	8062	9158	$\bar{0}285$					
83	8·1443	2636	3863	5126	6427	7769	9152	$\bar{0}579$	2052	3572					
84	9·514	9·677	9·845	10·02	10·20	10·39	10·58	10·78	10·99	11·20					
65	11·43	11·66	11·91	12·16	12·43	12·71	13·00	13·30	13·62	13·95					
86	14·30	14·67	15·06	15·46	15·89	16·35	16·83	17·34	17·89	18·46					
87	19·08	19·74	20·45	21·20	22·02	22·90	23·86	24·90	26·03	27·27					
88	28·64	30·14	31·82	33·69	35·80	38·19	40·92	44·07	47·74	52·08					
69	57·29	63·66	71·62	81·85	95·49	114·6	143·2	191·0	286·5	573·0					

$$1 \text{ ohm} = 10^9 \text{ e.m.u.} = \frac{1}{9\times 10^{11}} \text{ e.s.u.}$$

$$1 \text{ farad} = 10^9 \text{ e.m.u.} = 9\times 10^{11} \text{ e.s.u.}$$

$$1 \text{ microfarad} = 10^{-15} \text{ e.m.u.} = 9\times 10^{5} \text{ e.s.u.}$$

$$1 \text{ henry} = 10^9 \text{ e.m.u.} = \frac{1}{9\times 10^{11}} \text{ e.s.u.}$$